Searching for Ultralight Axions with Black Holes and Gravitational Waves

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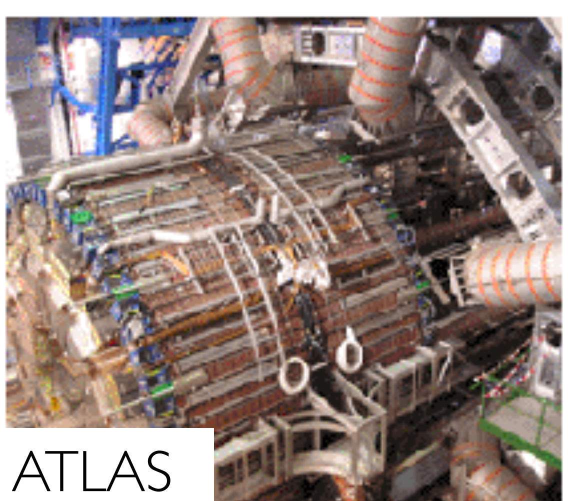
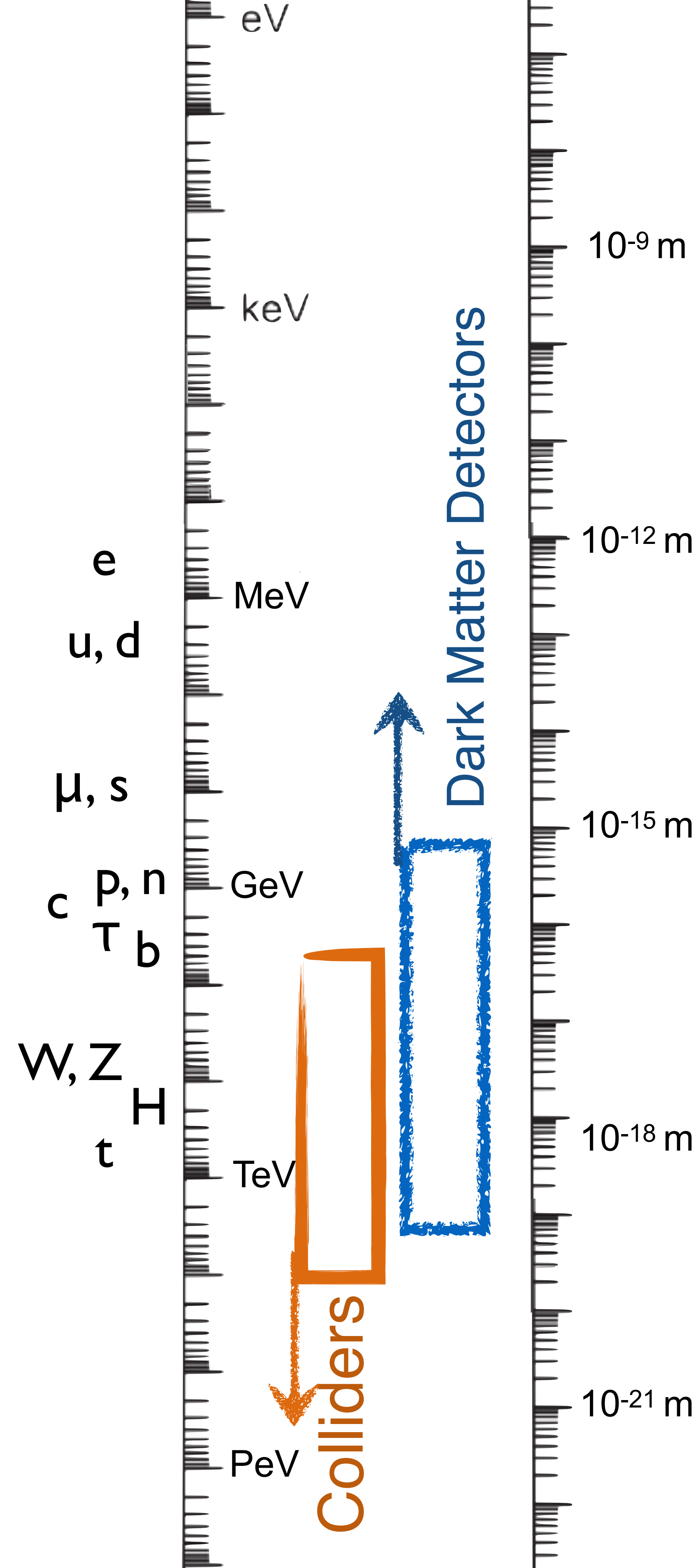
Searching for New Physics

- The Standard Model is very successful but incomplete
- Most of the standard model lies within several orders of magnitude in mass
- Other scales must enter in a complete theory

Colliders

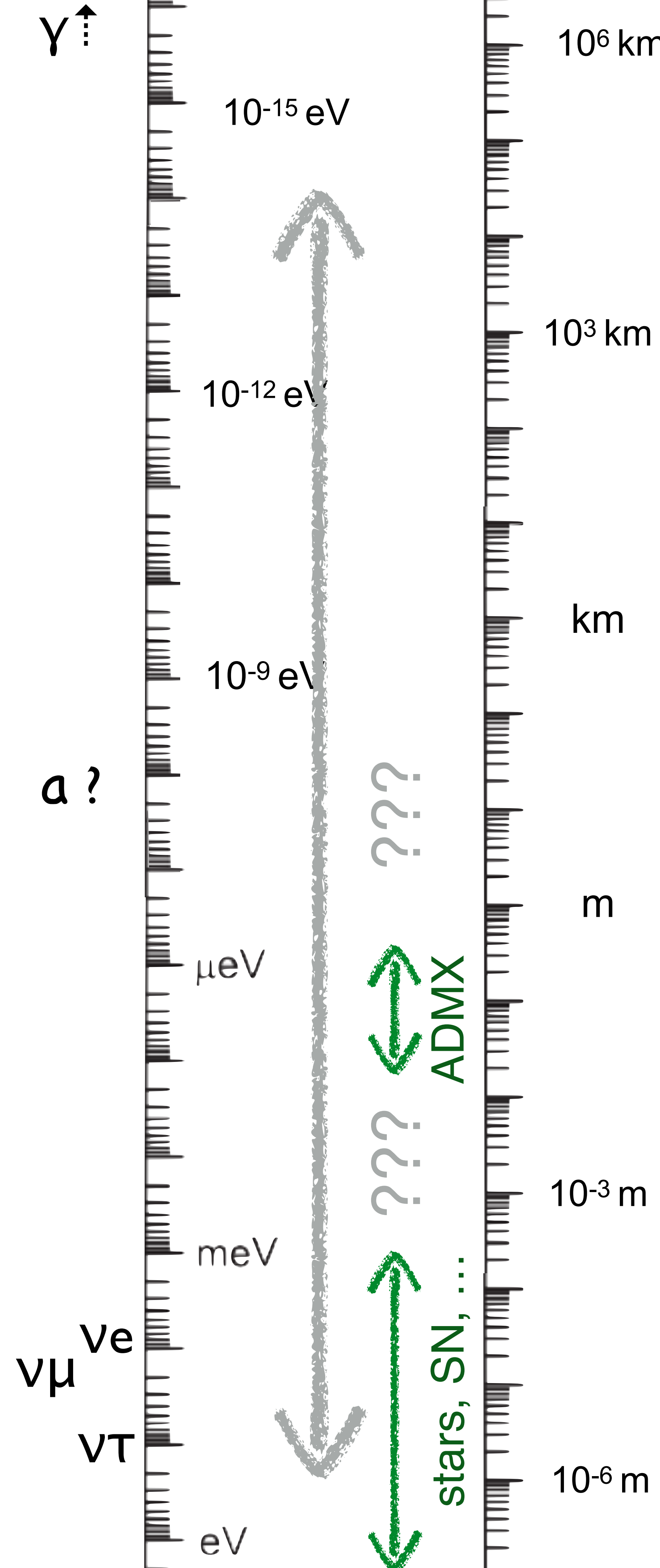


Dark Matter Detectors

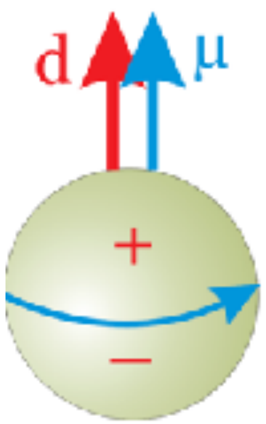


Searching for New Physics

- The Standard Model is very successful but incomplete
- Most of the standard model lies within several orders of magnitude in mass
- Other scales must enter in a complete theory
- Outstanding problems motivate searches at low energies
- Dark matter, strong-CP problem,…
    - QCD axion
        - Very weakly interacting
        - Long wavelength



The Strong-CP problem



- Theoretically expect significant CP violation in potential of strong interactions
- Upper bound from measurements of neutron electric dipole moment,

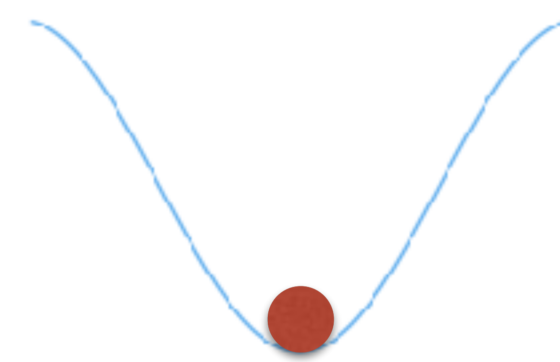
$$\theta_0 + \arg\det M_q + < 10^{-10}$$

- Solve the problem by promoting θ to a dynamical field, the **axion:**

$$V \supset \frac{\alpha_s}{8\pi}\,\theta\, G\,\tilde{G}$$

$$\downarrow$$

$$V \supset \frac{\alpha_s}{8\pi}\left(\frac{a}{f} - \theta\right) G\,\tilde{G}$$



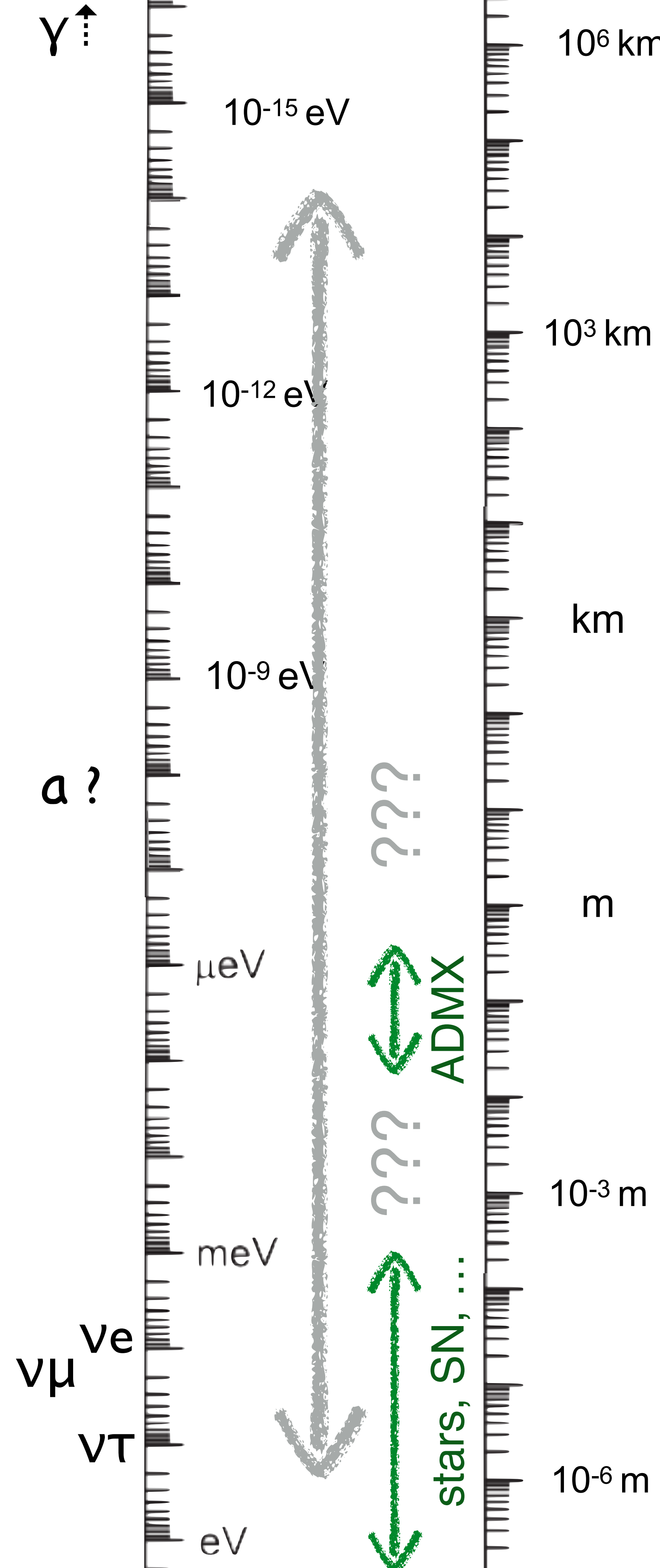
- Nonperturbative QCD effects create potential for the axion; at the minimum the strong-CP problem is solved

Peccei and Quinn, PRL 38, 1440, 1977
Weinberg, PRL 40, 223, 1978
Wilczek, PRL 40, 279, 1978

Searching for New Physics

- Axions are
  - Solutions to a theoretical puzzle of small numbers—the strong-CP problem.
  - Approximately massless particle with mass and couplings fixed by a high scale f_a,

$$\mu_a \simeq 6 \times 10^{-12}\text{eV}\left(\frac{10^{18}\text{GeV}}{f_a}\right)$$



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    - Low-energy remnants of complex physics at high scales   Svrcek , Witten
      Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell
    - Candidates for the dark matter of the universe   Preskill, Wise, Wilczek
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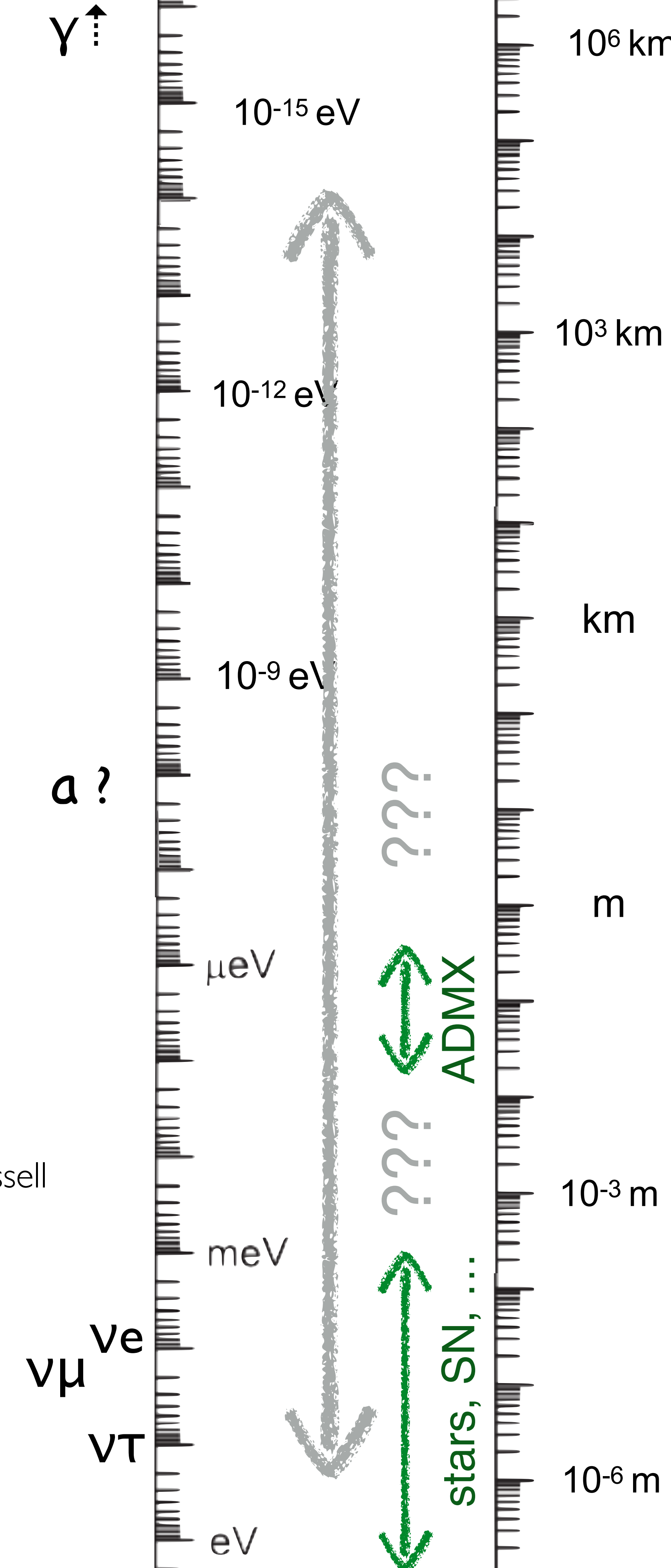

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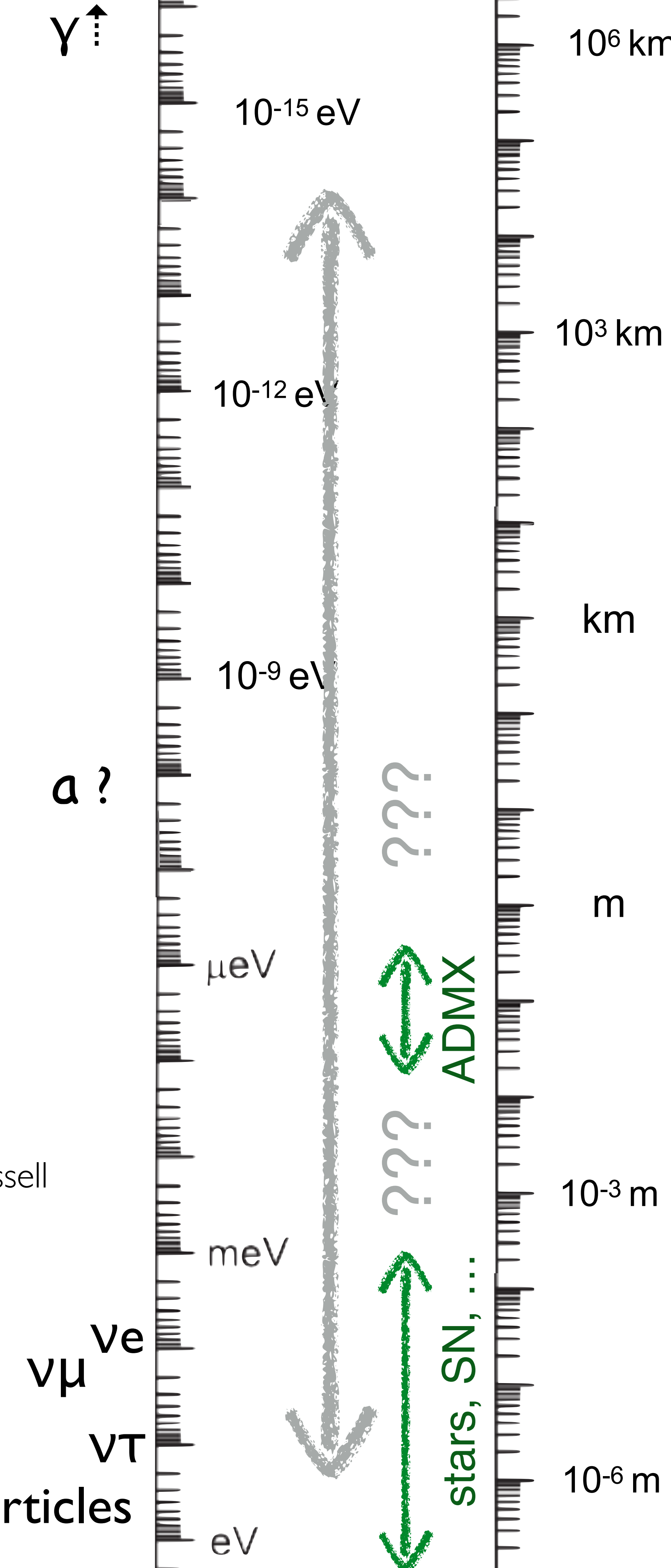
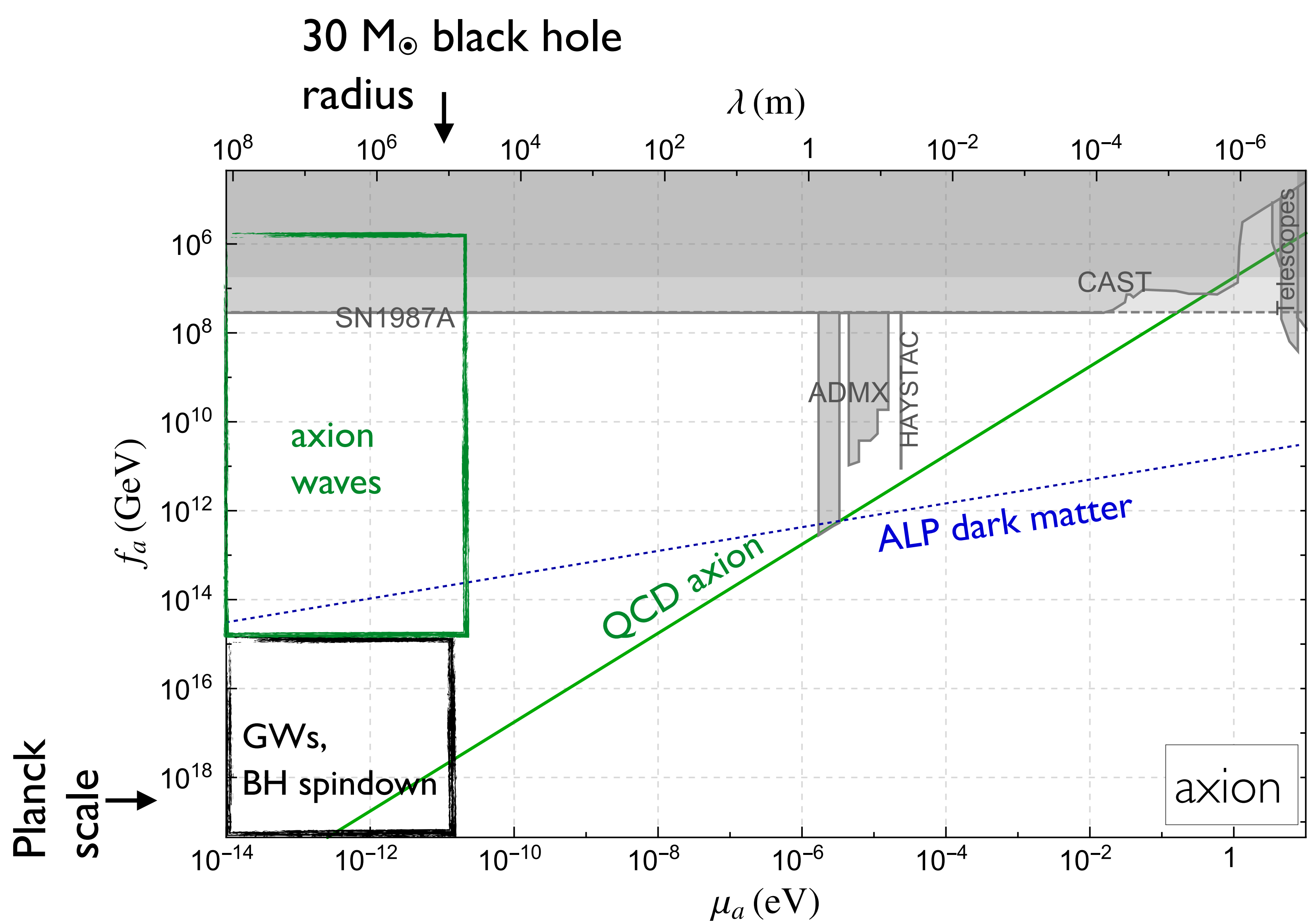
more general axion like particles



Black holes can teach us about these light, weakly interacting particles

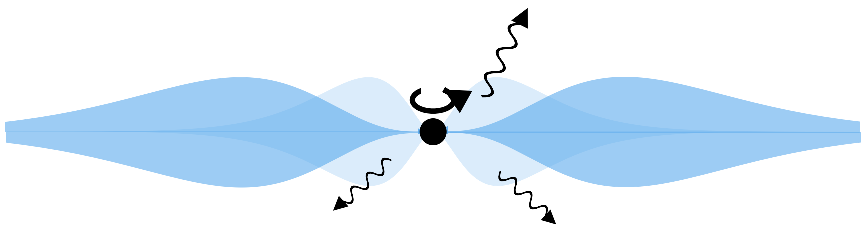
Ultralight Axions and Black Holes

- Rotating black holes can source `clouds' of weakly coupled bosons
- QCD axion which solves the `strong-CP' problem in particle physics and axion-like particles particularly well-motivated candidates for these searches
- Axion-like particles motivate a broader parameter space



Outline

- Black hole superradiance

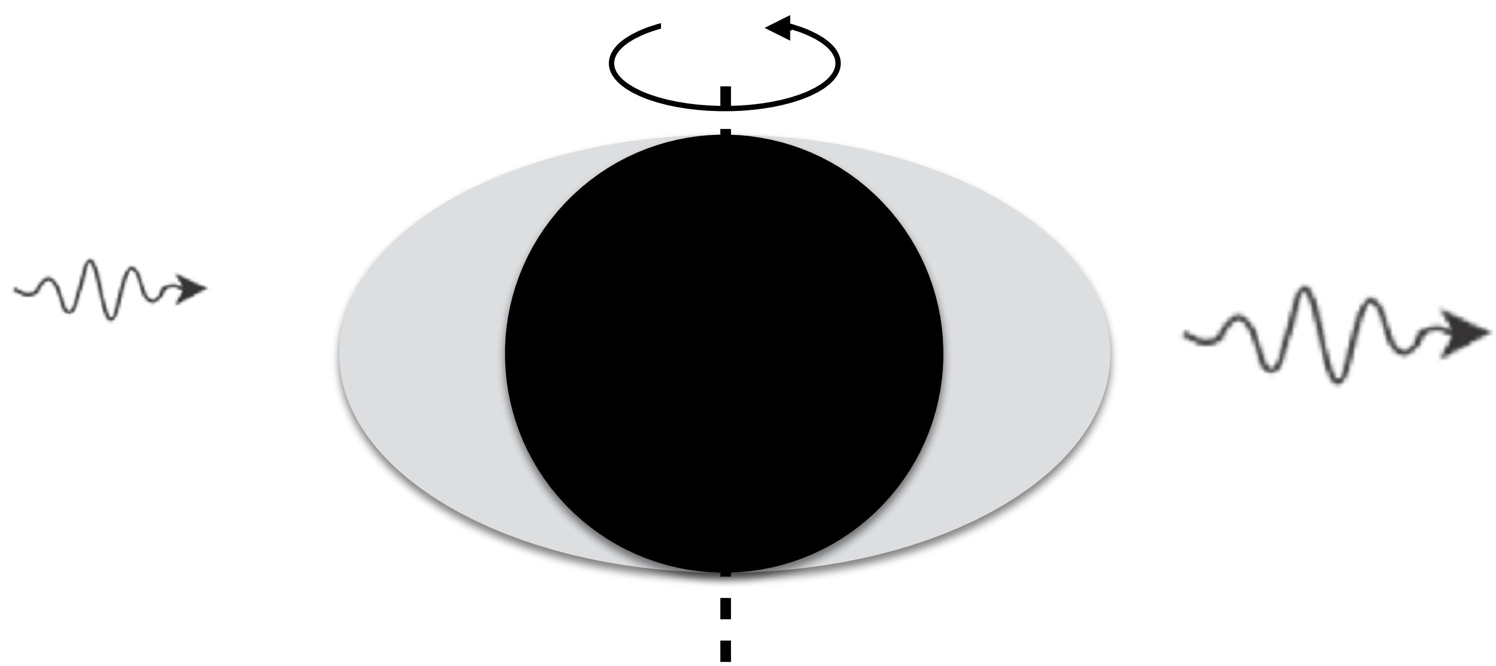


- Gravitational searches for new particles

- Self interactions and axion waves

Superradiance

- A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.
- Growth proportional to probability of absorption when rotating object is at rest: **dissipation** necessary to increase wave amplitude



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

Zel'dovich; Starobinskii; Misner

Superradiance

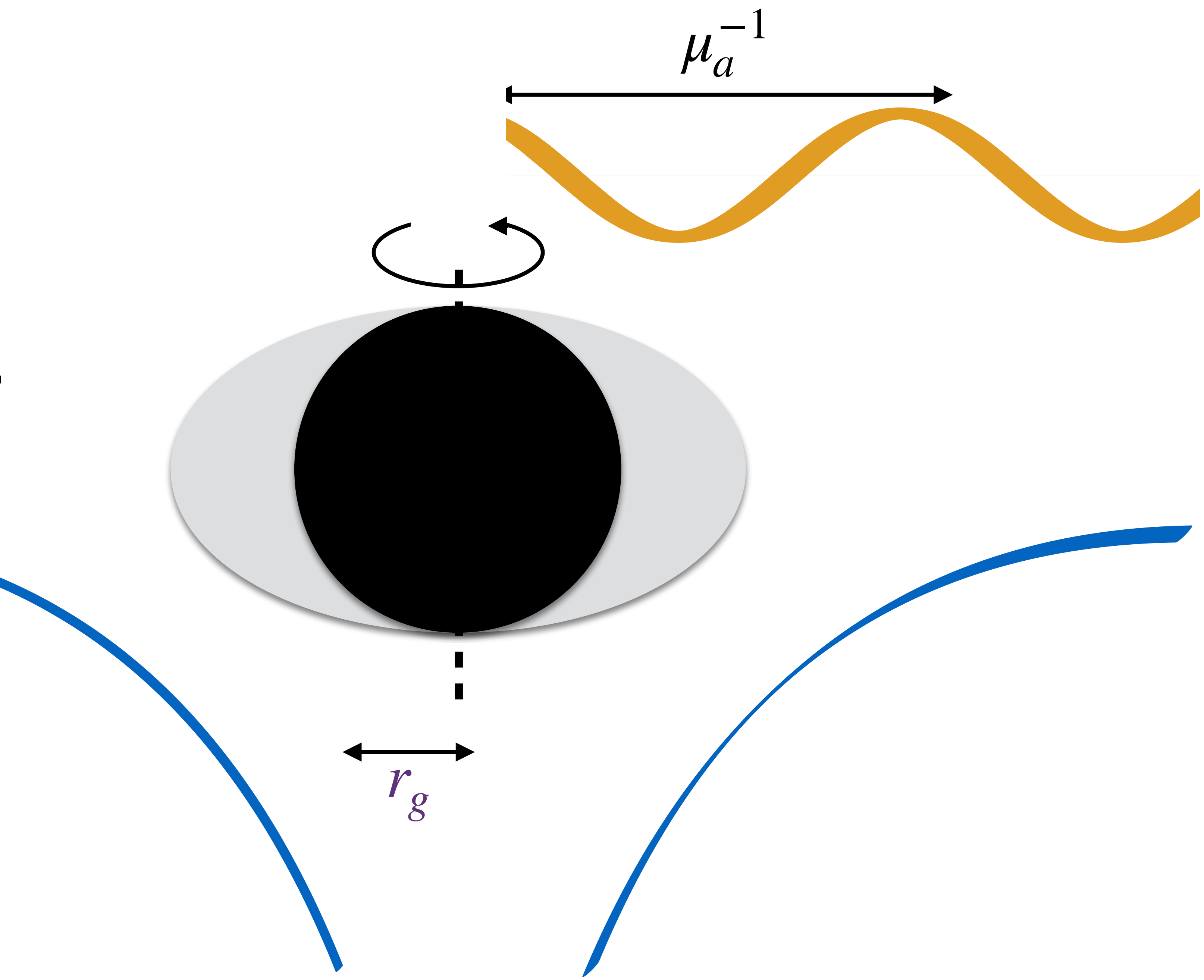
- Particles/waves trapped near the BH repeat this process continuously

- For a massive particle, e.g. axion, gravitational potential barrier provides trapping

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$

- For high superradiance rates, compton wavelength should be comparable to black hole radius:

$$r_g \lesssim \mu_a^{-1} \sim 3\,\mathrm{km}\,\frac{6\times10^{-11}\mathrm{eV}}{\mu_a}$$

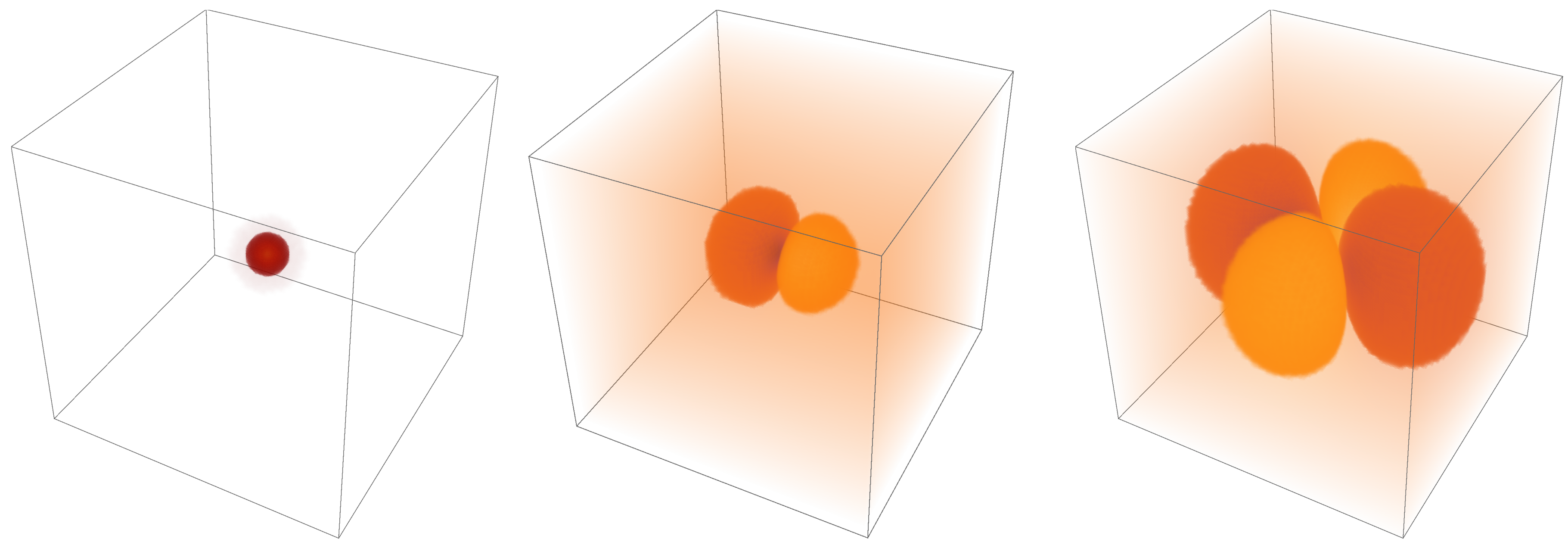


Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78
Tool to search for axions: Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010

Gravitational Atoms

Axion Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$



$n = 1, \ell = 0, m = 0$ $n = 2, \ell = 1, m = 1$ $n = 3, \ell = 2, m = 2$

Gravitational potential similar to hydrogen atom

`Fine structure constant`

$$\alpha \equiv G_N M_{BH} \mu_a \equiv r_g \mu_a$$

Radius

$$r_c \simeq \frac{n^2}{\alpha\, \mu_a} \sim 4 - 400 r_g$$

Occupation number

$$N \sim 10^{75} - 10^{80}$$

Gravitational Atoms

Axion
Gravitational Atoms

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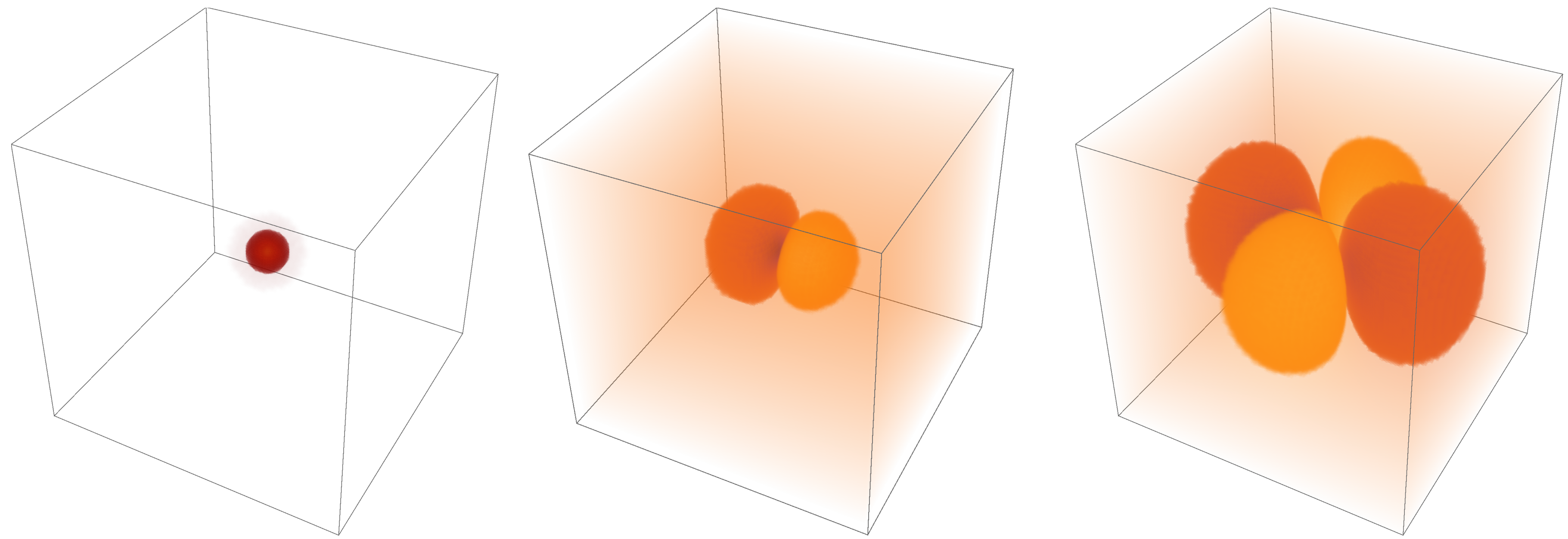

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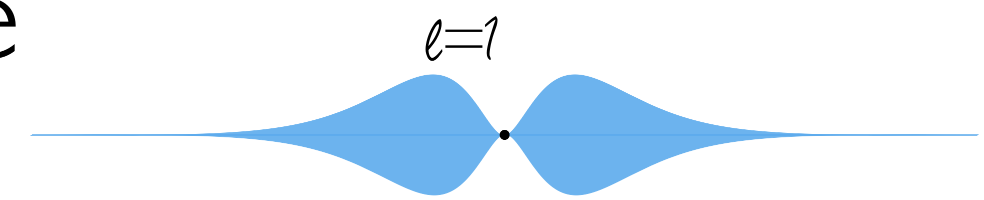
Boundary conditions at horizon give imaginary frequency:

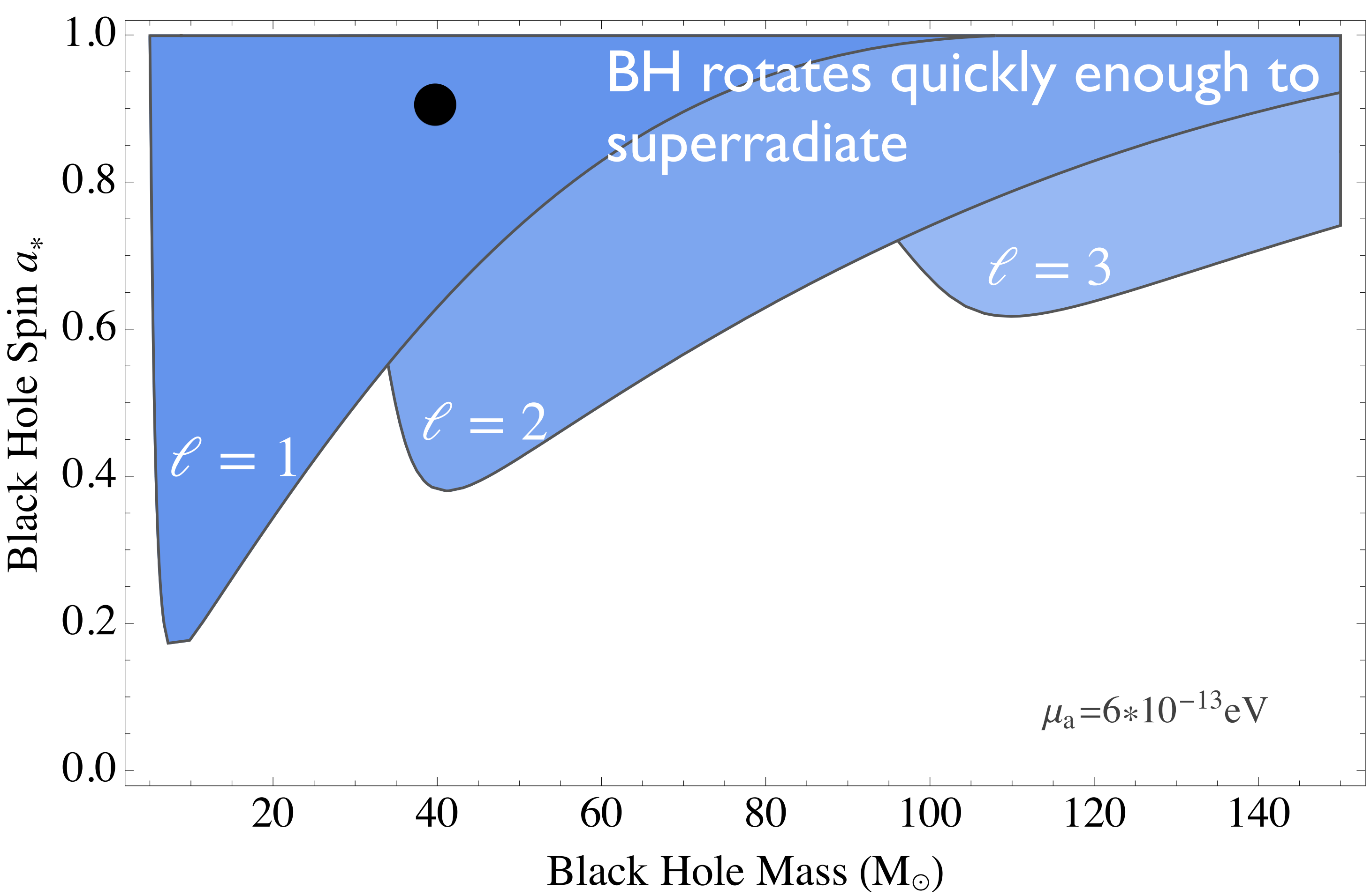
$$E \simeq \mu \left(1 - \frac{\alpha^2}{2n^2} \right) + i\Gamma_{\rm sr}$$

exponential growth of particle number in states satisfying superradiance condition

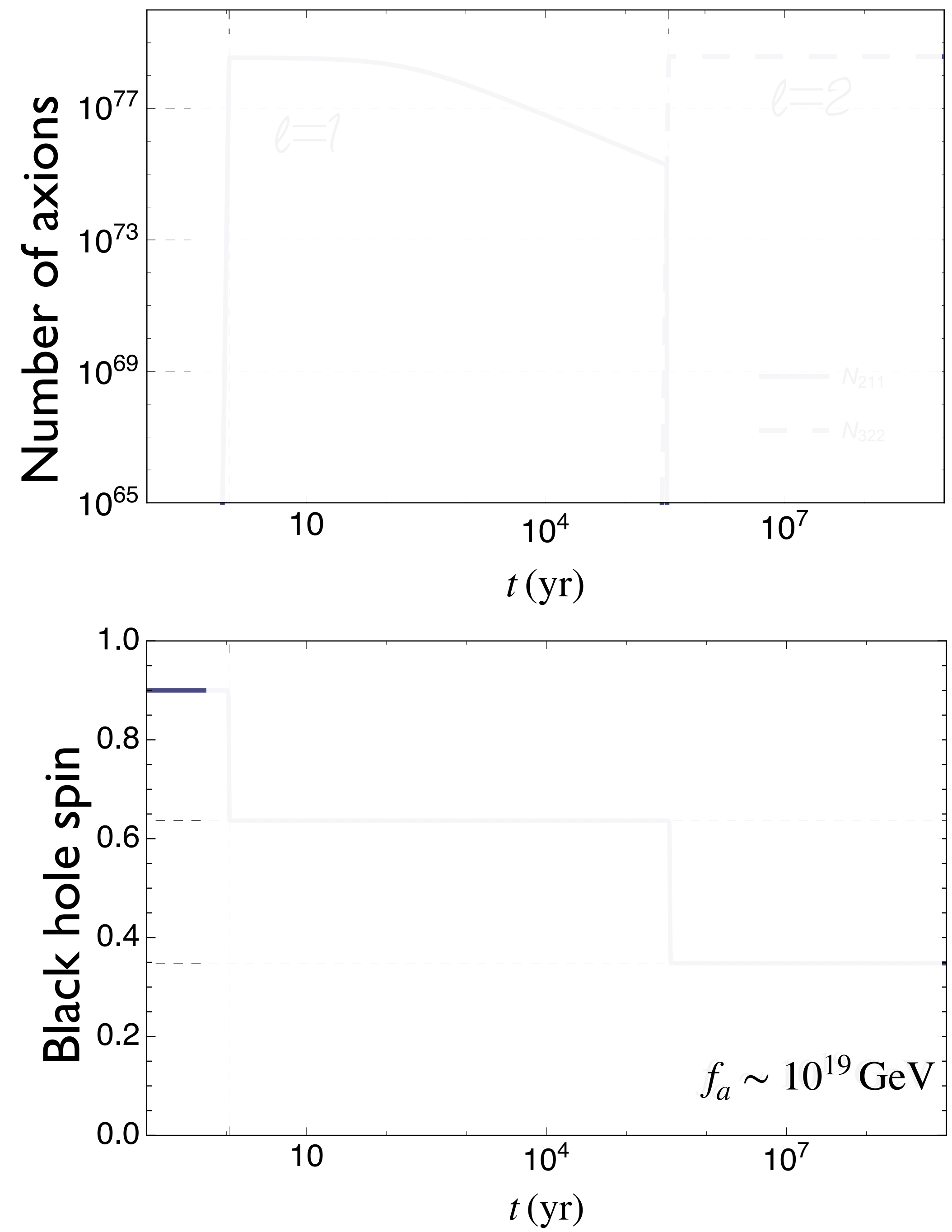
Superradiance



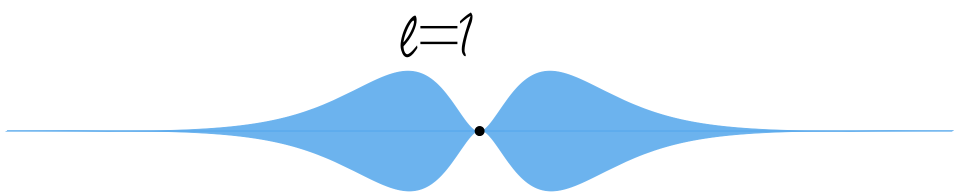
- If new light axions exist, fast-spinning black holes will superradiate: lose energy and angular momentum to exponentially growing bound states of axions



Time evolution



Superradiance



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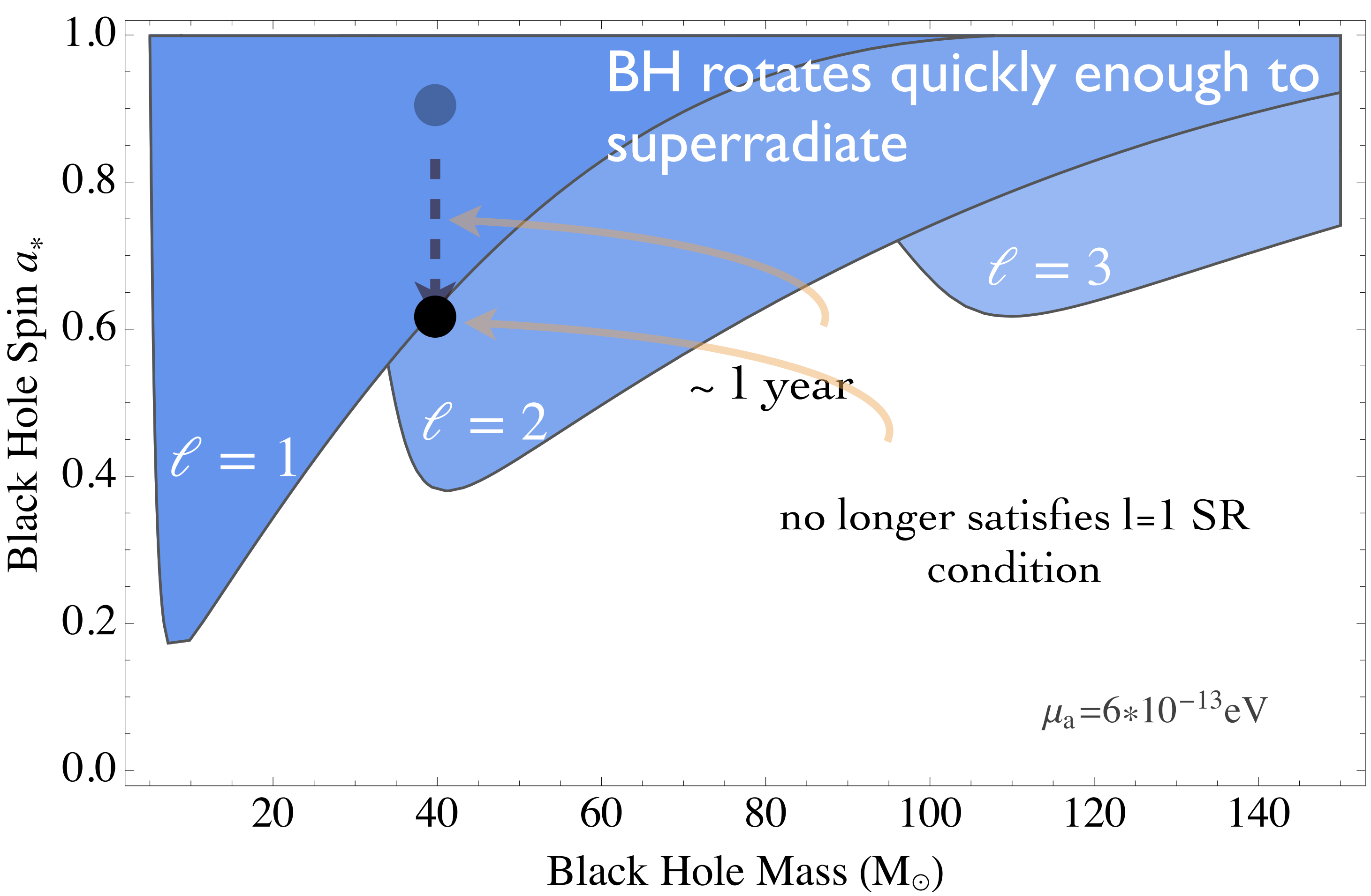

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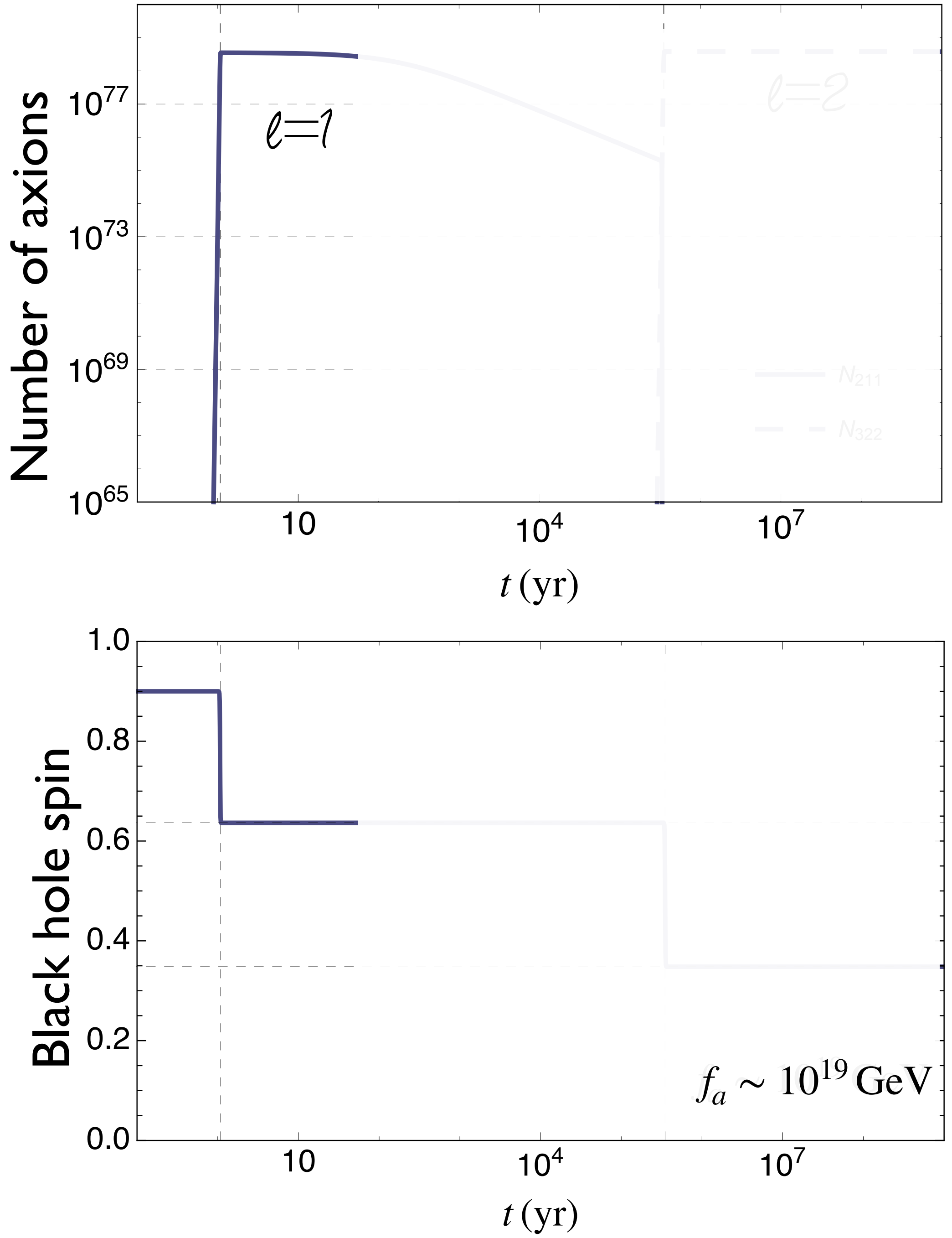
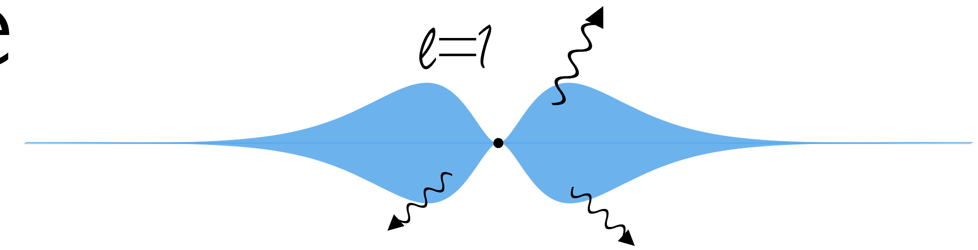
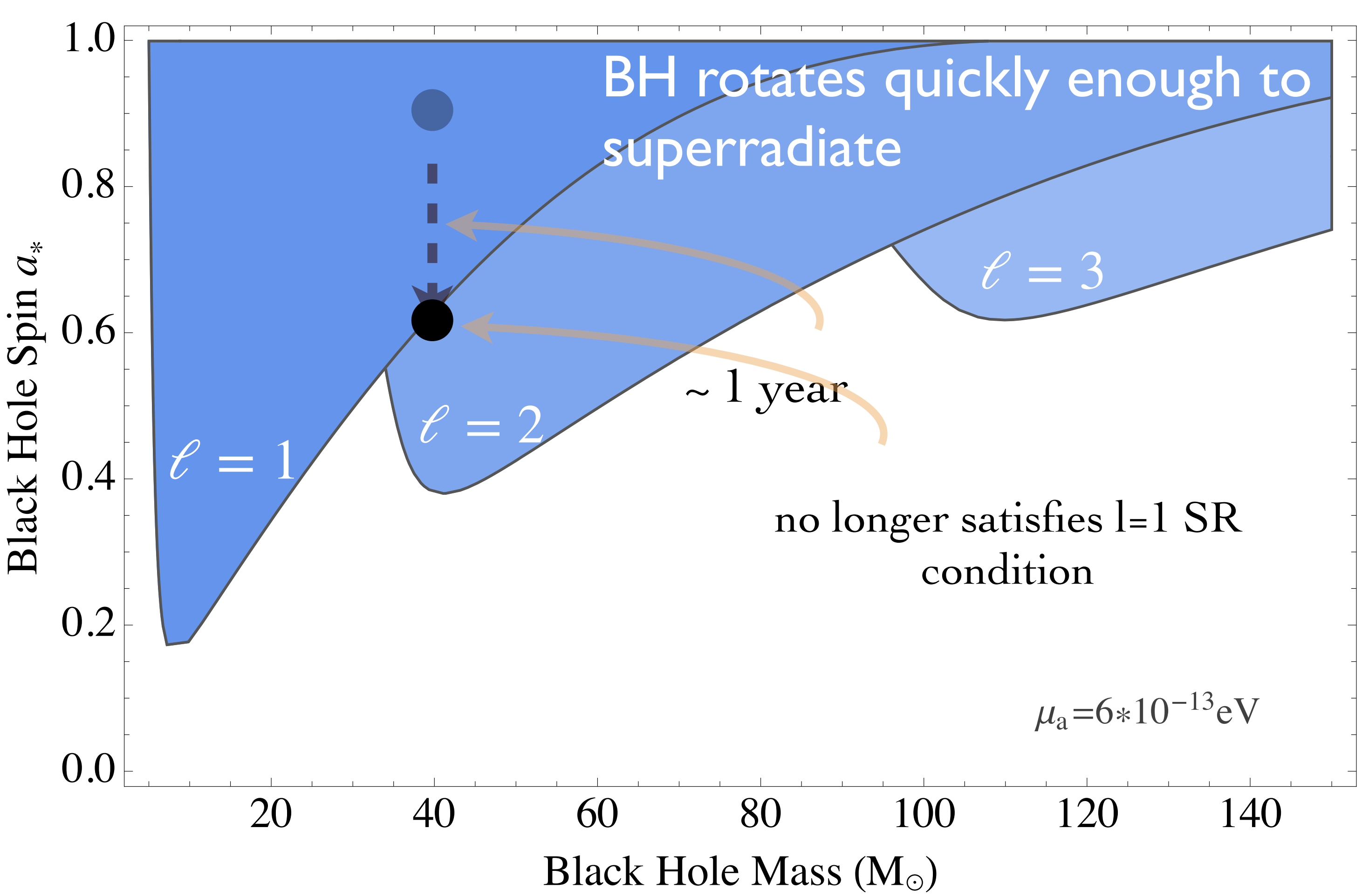


Superradiance



- Large energy density in the cloud, with time dependence set by the axion mass
- Sources monochromatic gravitational wave radiation
- Axion cloud depletes on long timescales through GW emission



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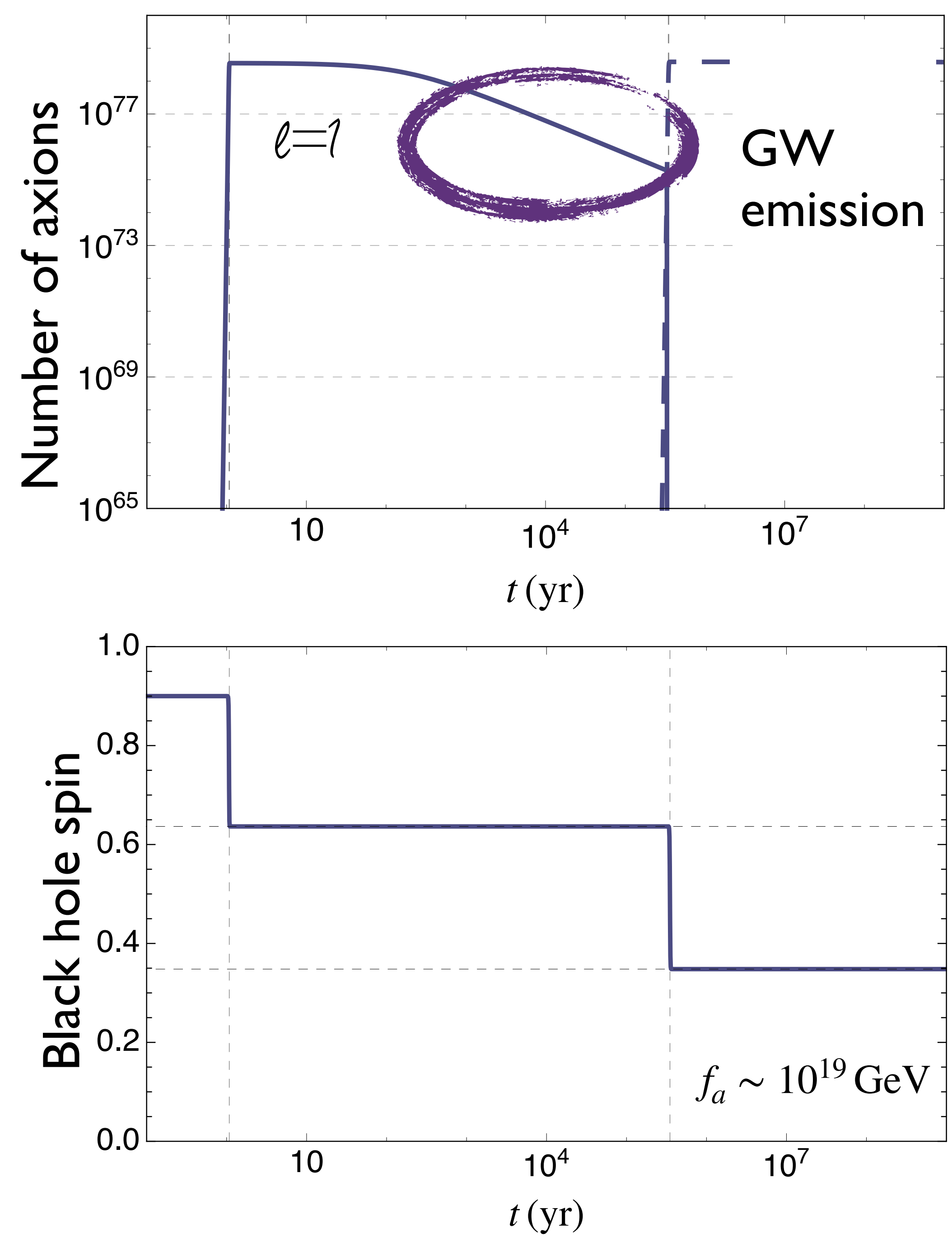

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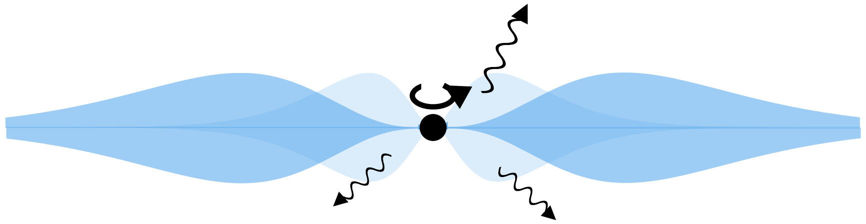

- Gravitational searches for new particles

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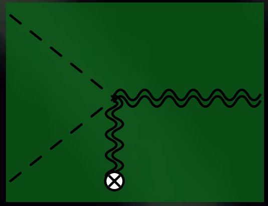
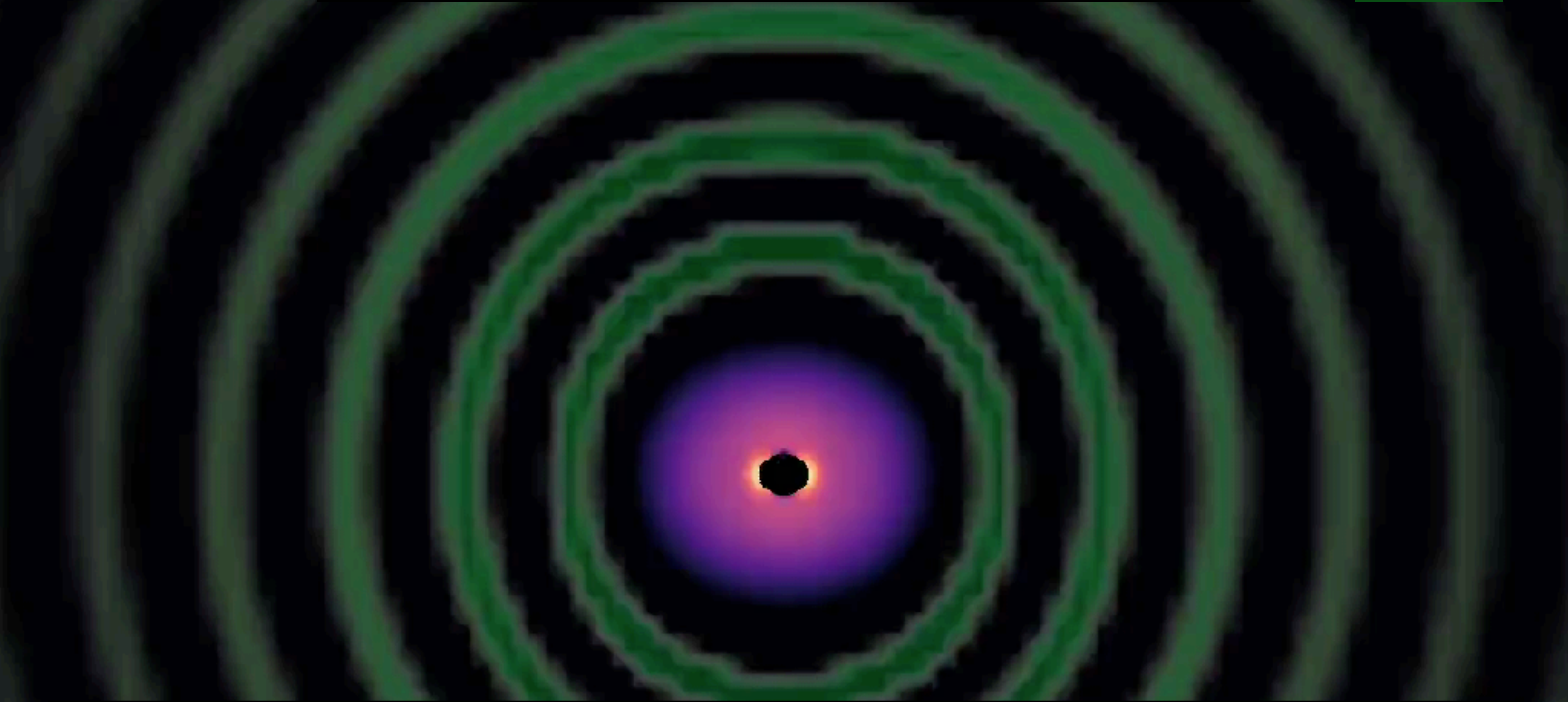
Gravitational Wave Signals





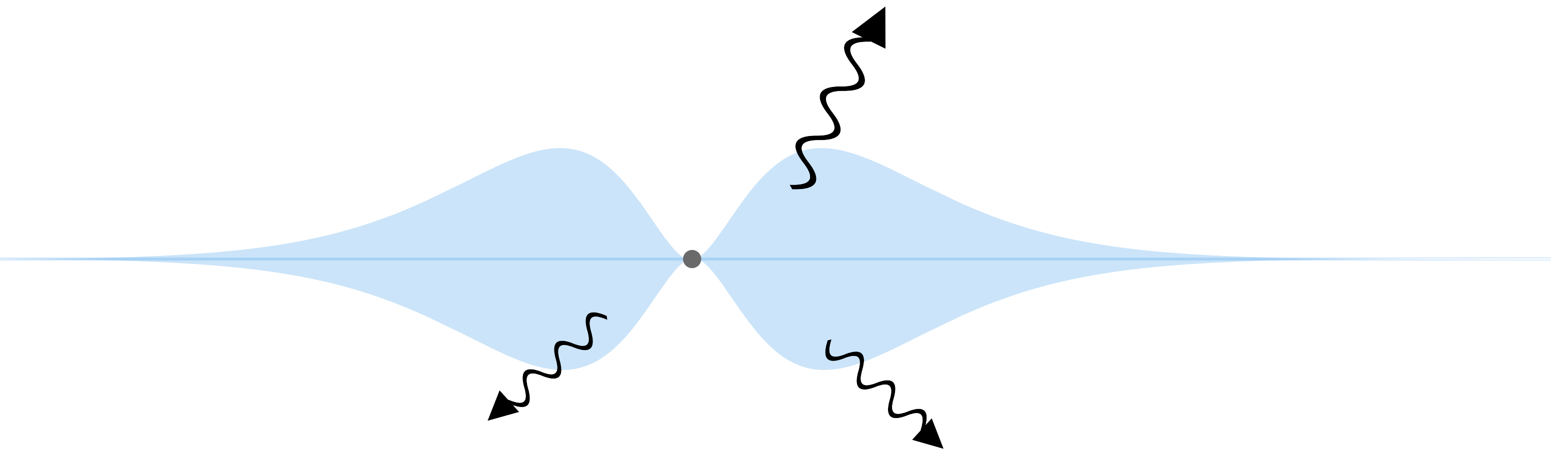
Time-varying energy density sources gravitational waves:

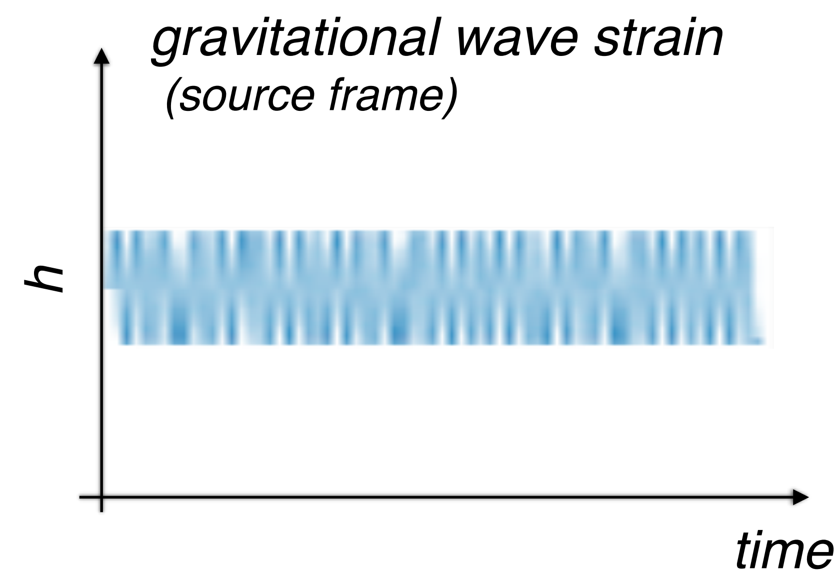
two bosons annihilating into gravitational waves

- coherent and monochromatic:
- fit into searches for long, continuous, monochromatic gravitational waves ("mountains" on neutron stars)

Numerical GR simulation by Will East (dark photon)

Gravitational Wave Signals

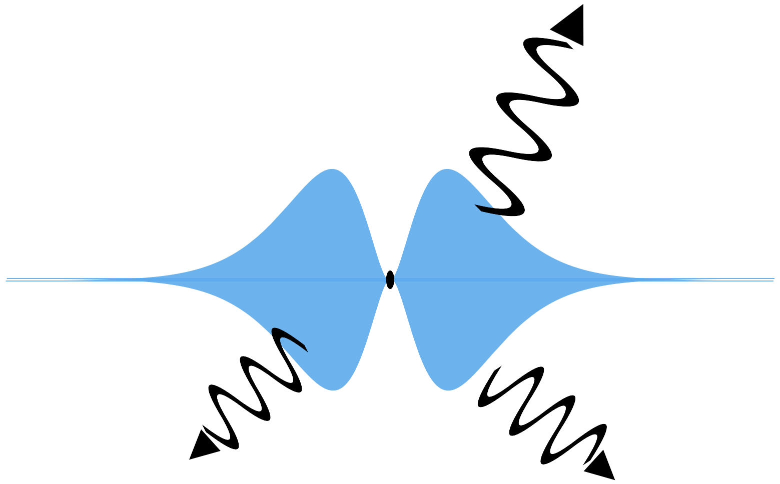


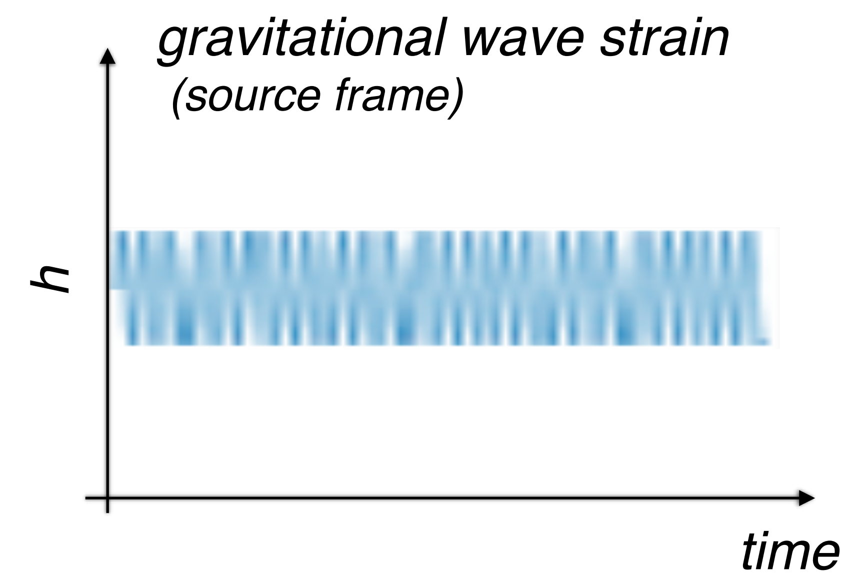


- **Weak, long signals** last for ~ thousand- billion years, visible from our galaxy
  - Event rates up to 10,000 — can be observed and studied in detail

Arvanitaki, **MB**, Huang (2015)
Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
Brito et al (2017)

Gravitational Wave Signals





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- **Loud, short signals** last for ~ days - months, observable from BBH or NS-NS merger events
  - Event rates <1/year at design aLIGO sensitivity, up to 100's at future observatories

Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
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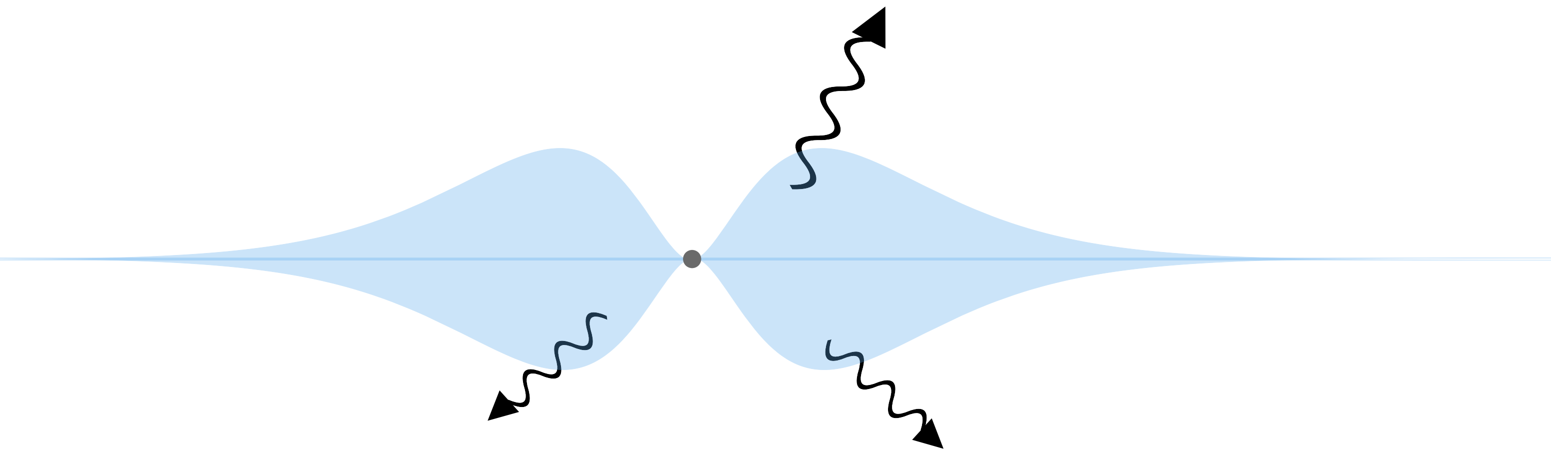

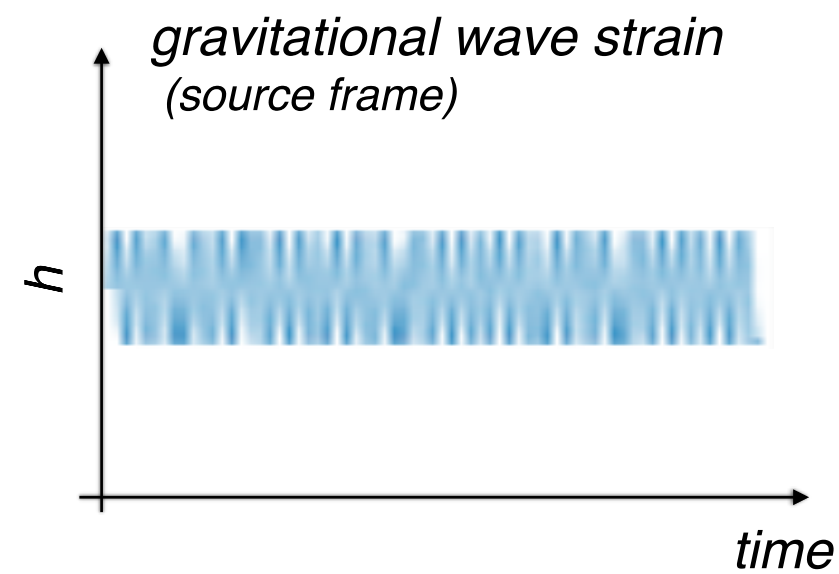

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Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2020)

what are the near-term prospects of detection?

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Arvanitaki, **MB**, Dimopoulos, Dubovsky, Lasenby (2017)
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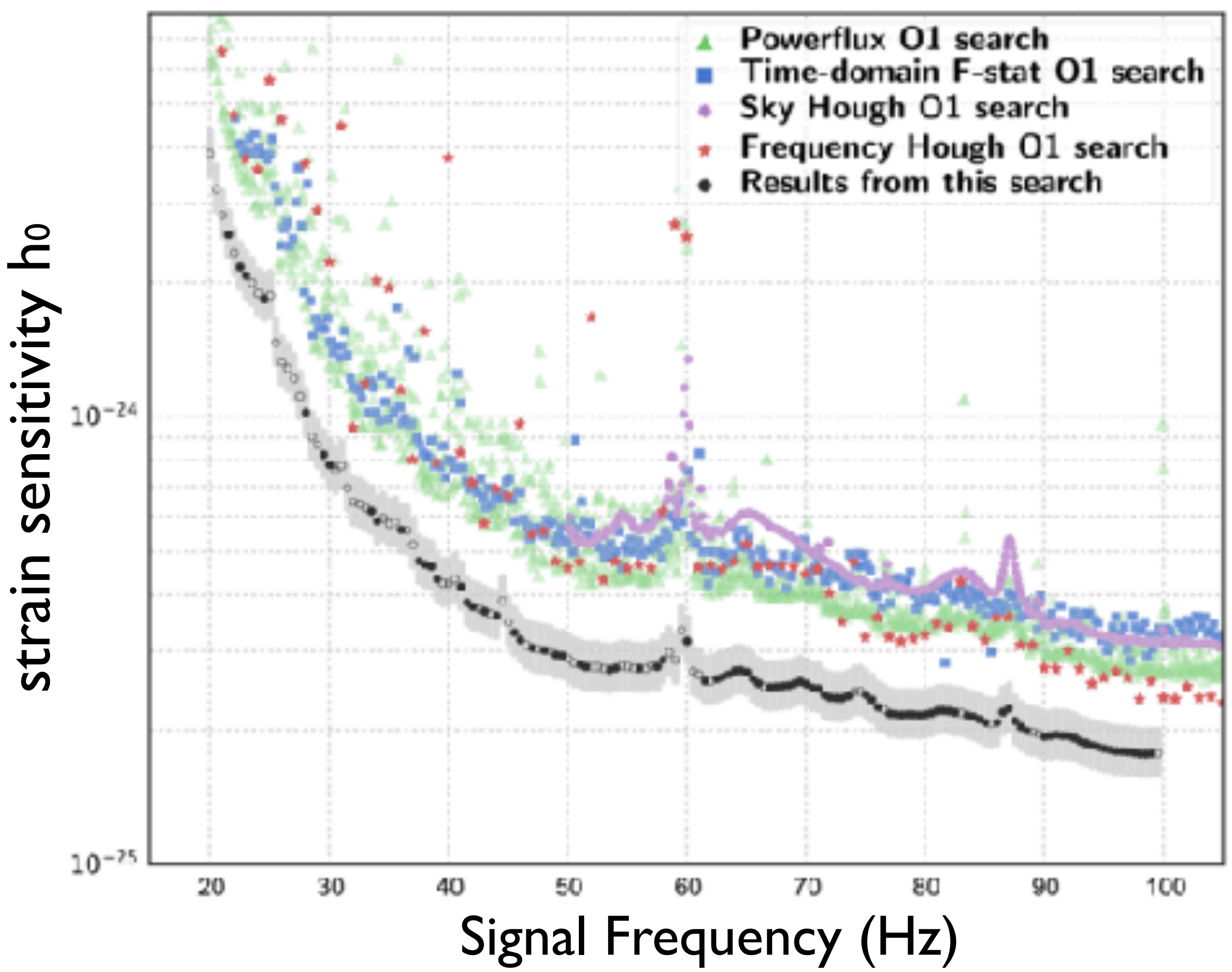
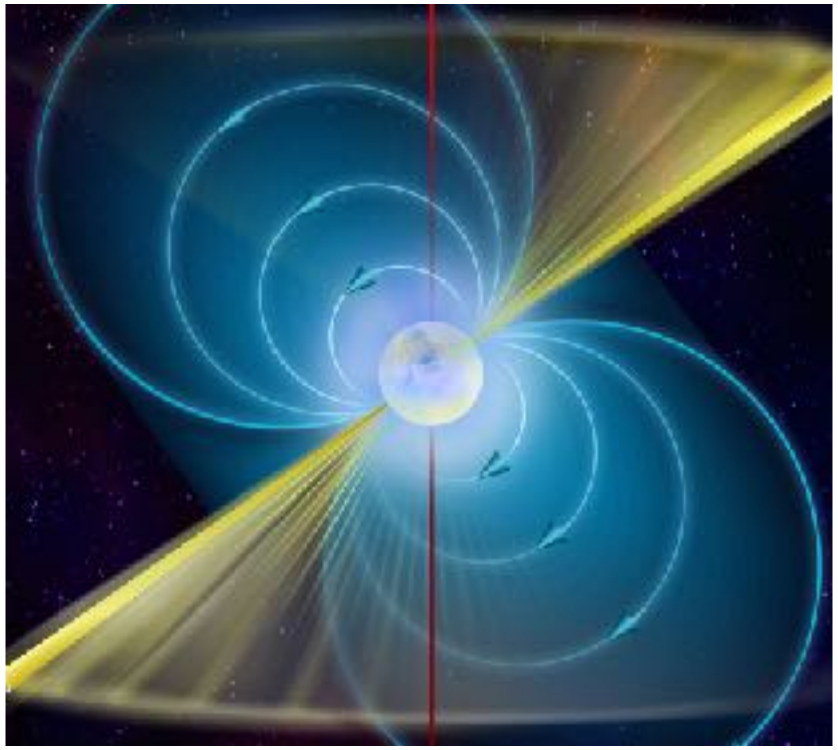
Gravitational Wave Searches

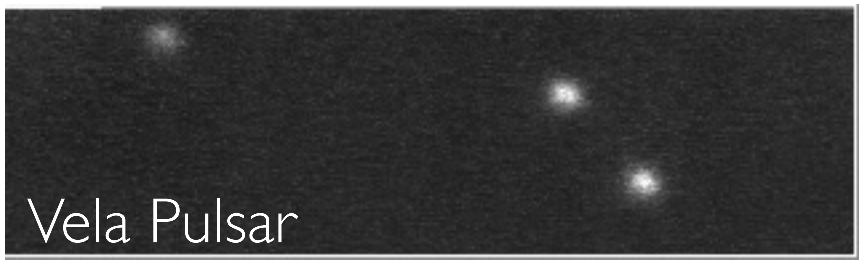
- Current searches for gravitational waves from asymmetric rotating neutron stars ongoing
- Targeted as well as all-sky searches, reaching to very weak signals with large computational efforts

All-Sky O1 Upper Limits



Abbott et al PRD 96, 122004 (2017)

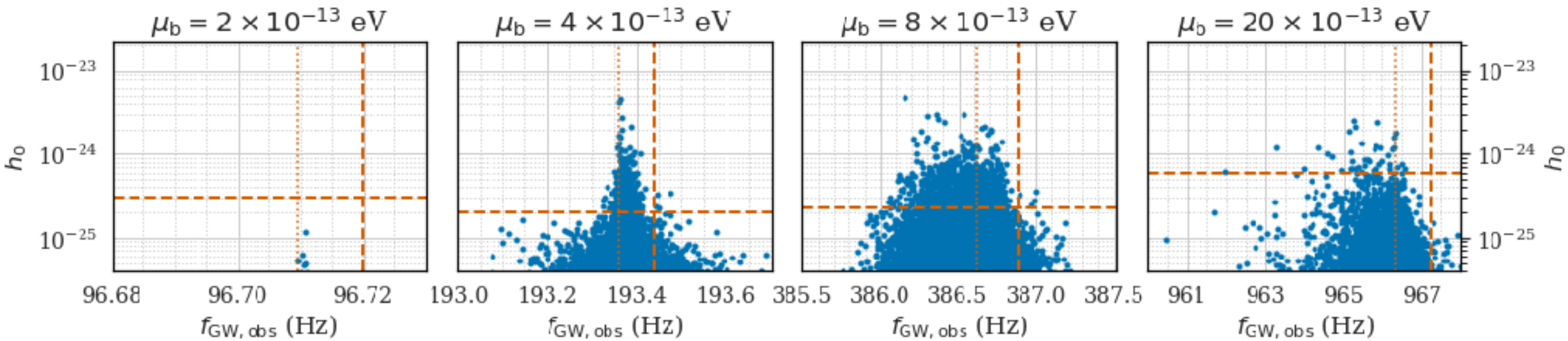




Cambridge University Lucky Imaging Group

Gravitational Wave Signals

- Simulated population of 10^8 black holes born in the Milky Way over age of universe
- Each can potentially grow a cloud of axions and subsequently source gravitational waves



Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

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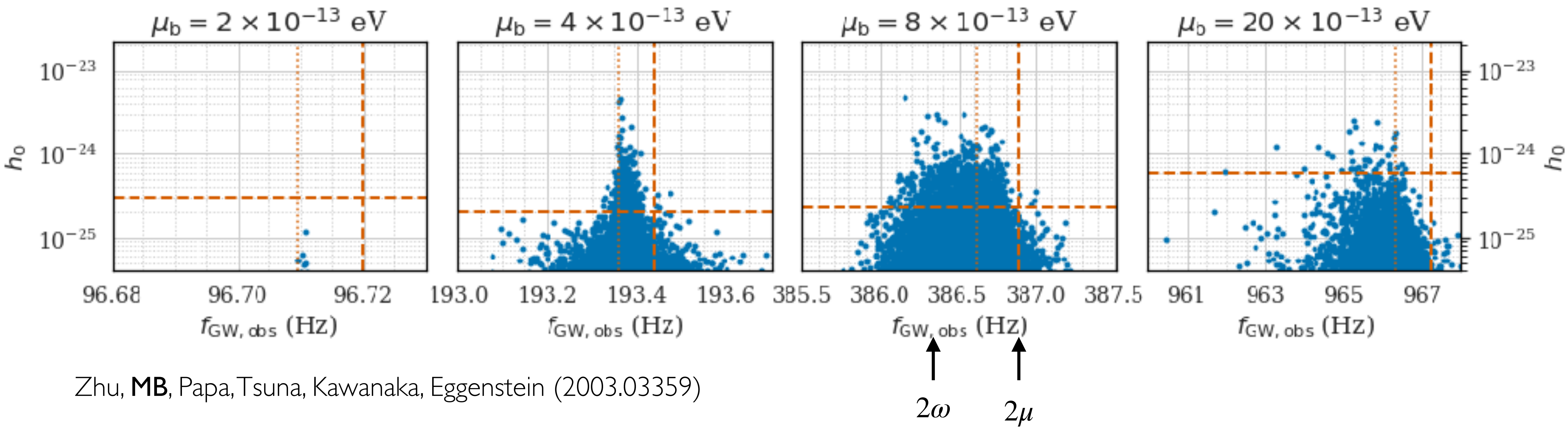


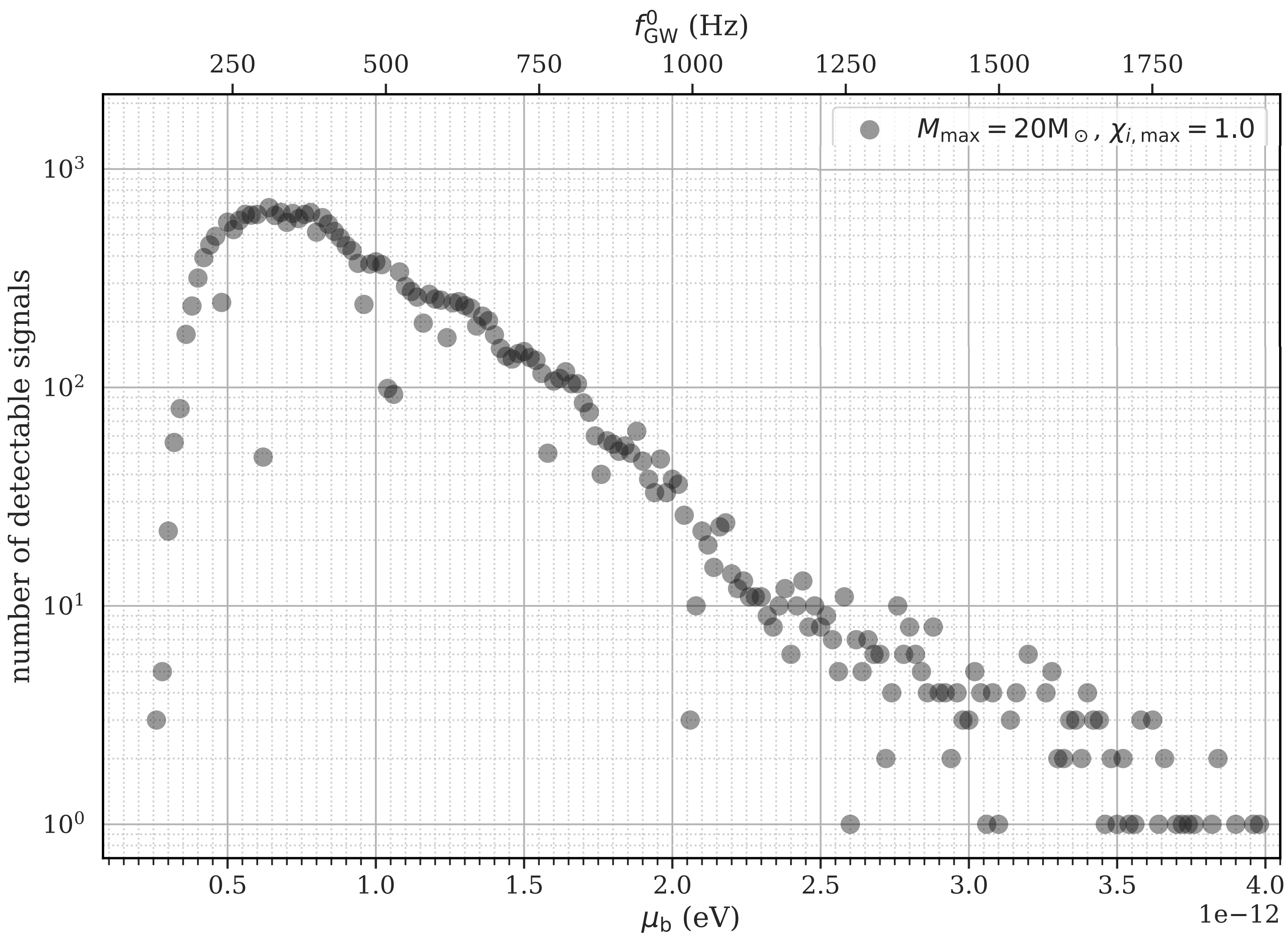
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

- Signals clustered at frequency ~twice the axion mass
- Binding energy and doppler shift detected frequency; heavier black holes produce larger signals, lower frequencies
- If one signal is detectable, expect many with a unique strain vs. frequency profile

Signal files available at: www.aei.mpg.de/continuouswaves/arxiv200303359

Gravitational Wave Searches

- Tens to thousands of events observable in current LIGO data depending on the axion mass



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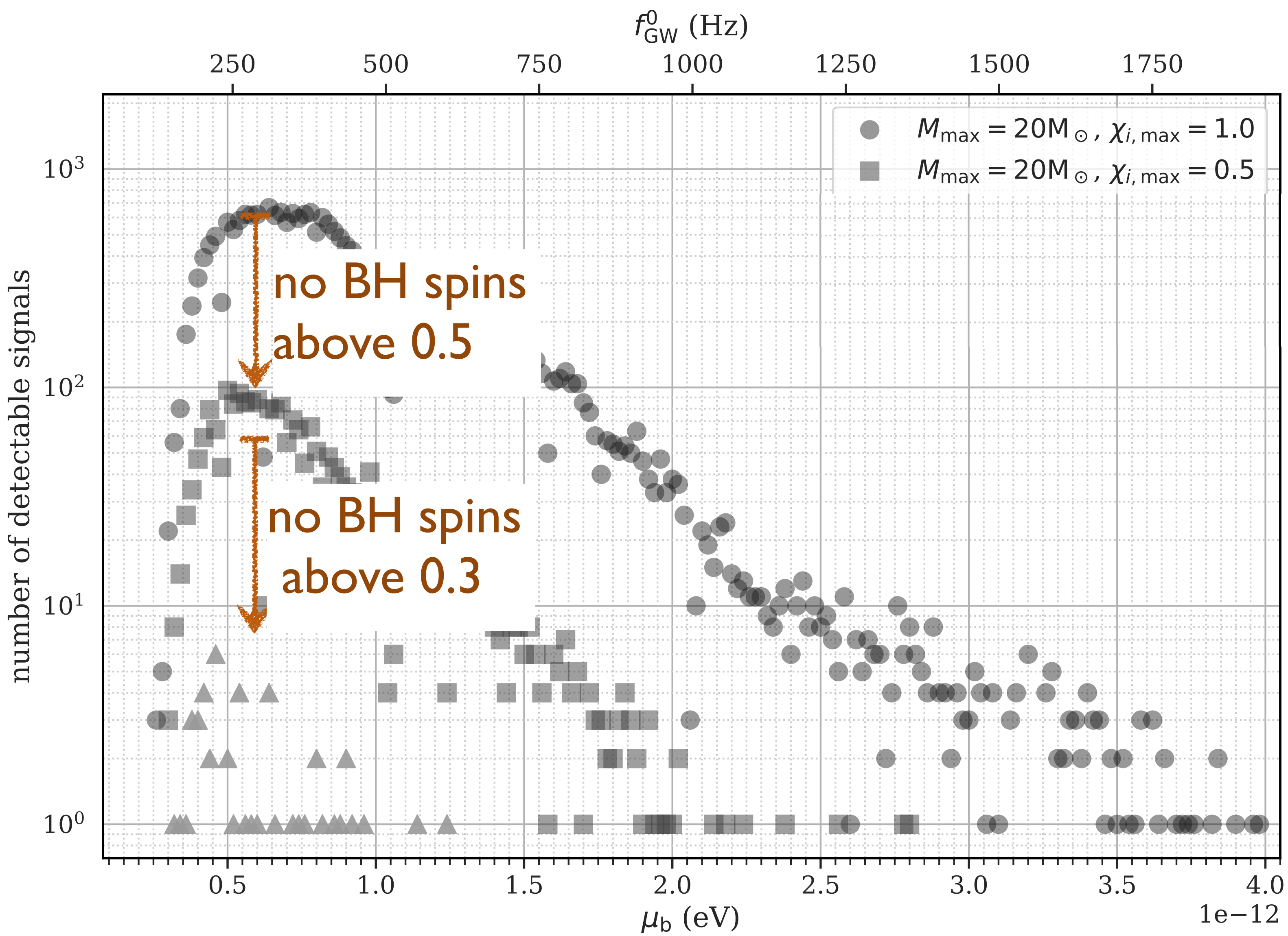

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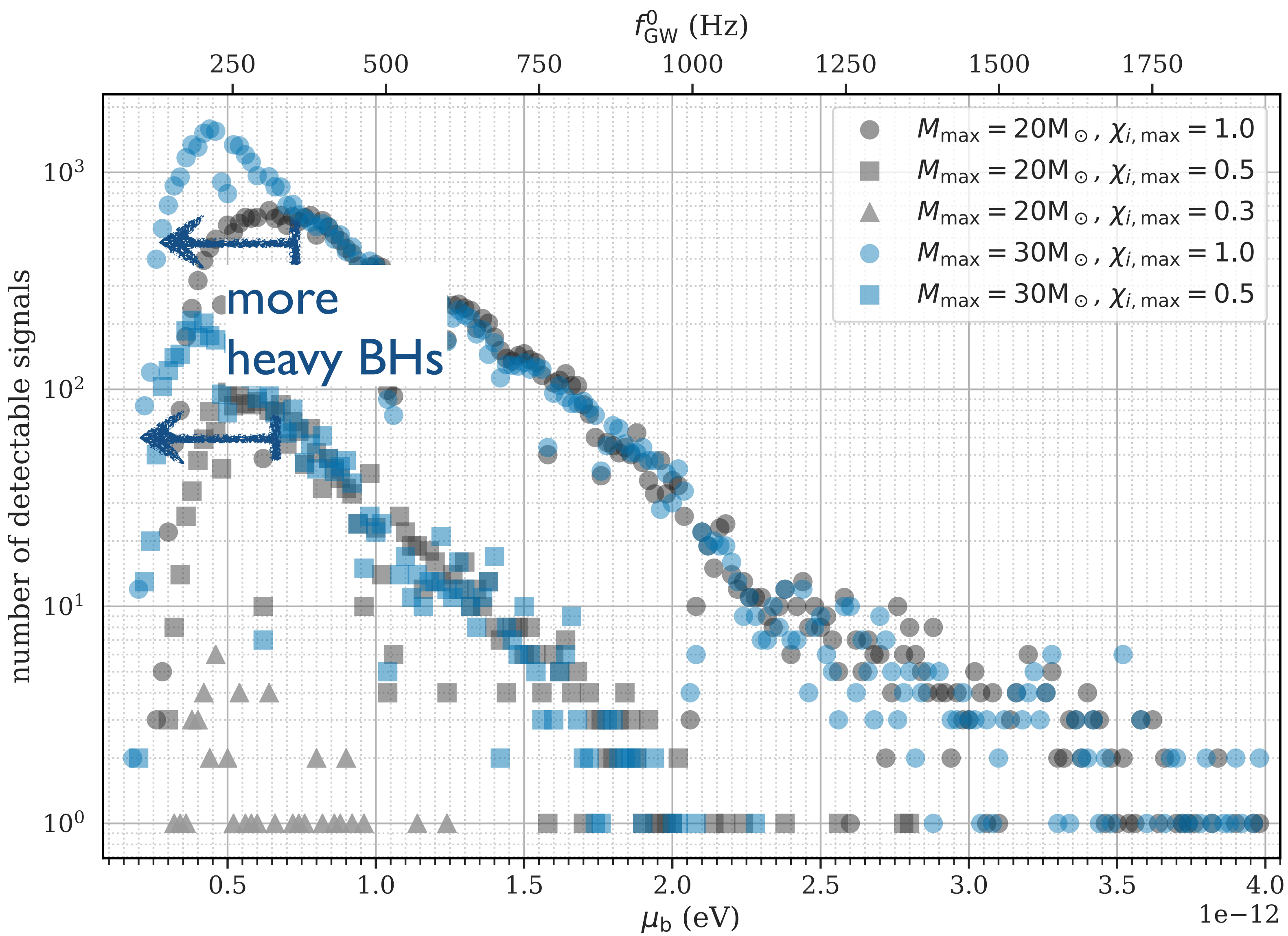

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- Weak dependence on mass distribution except at low axion masses

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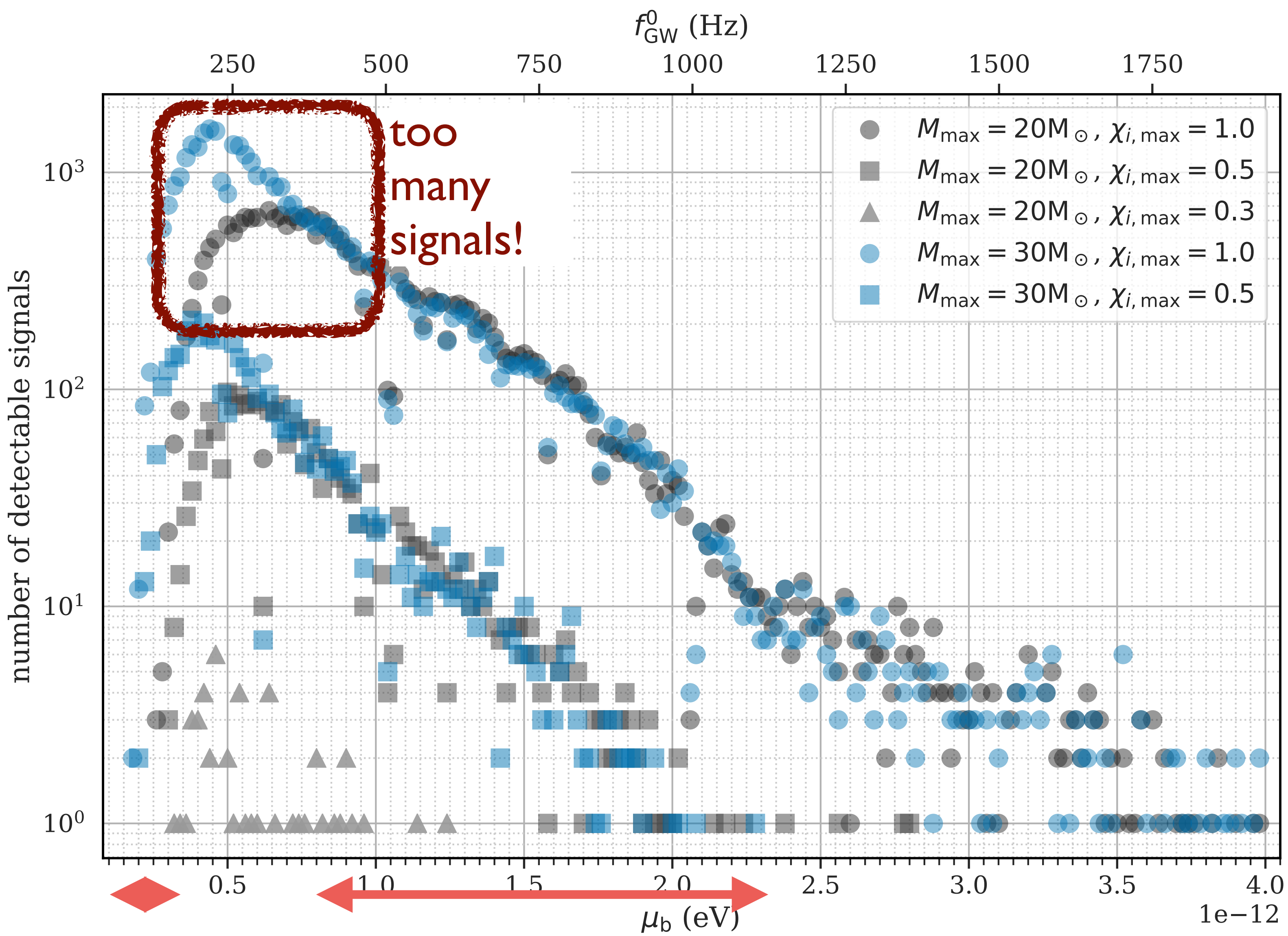

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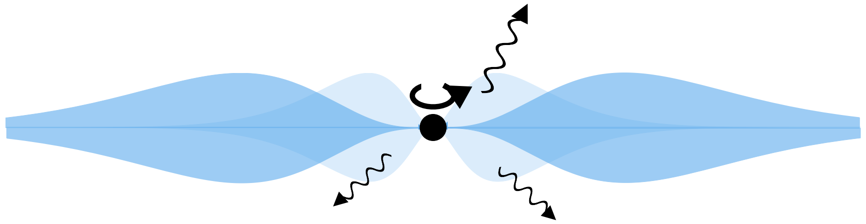
- Very sensitive to number of rapidly rotating black holes
- Weak dependence on mass distribution except at low axion masses

- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- Can disfavor axions of mass ~10^{-12} eV with existing LIGO sensitivity, given assumptions on black hole populations
- Further characterization of continuous wave searches in dense signal regime is ongoing

Outline

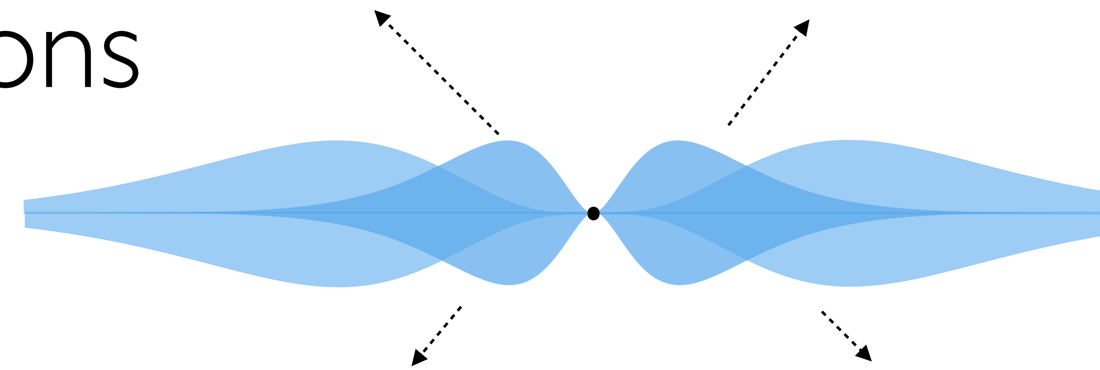
- Black hole superradiance



- Gravitational searches for new particles

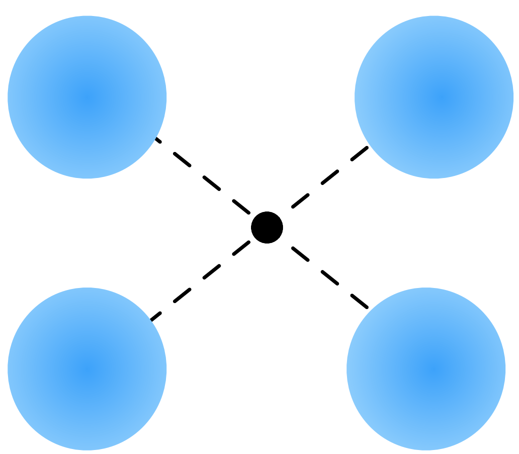
- Self interactions and axion waves

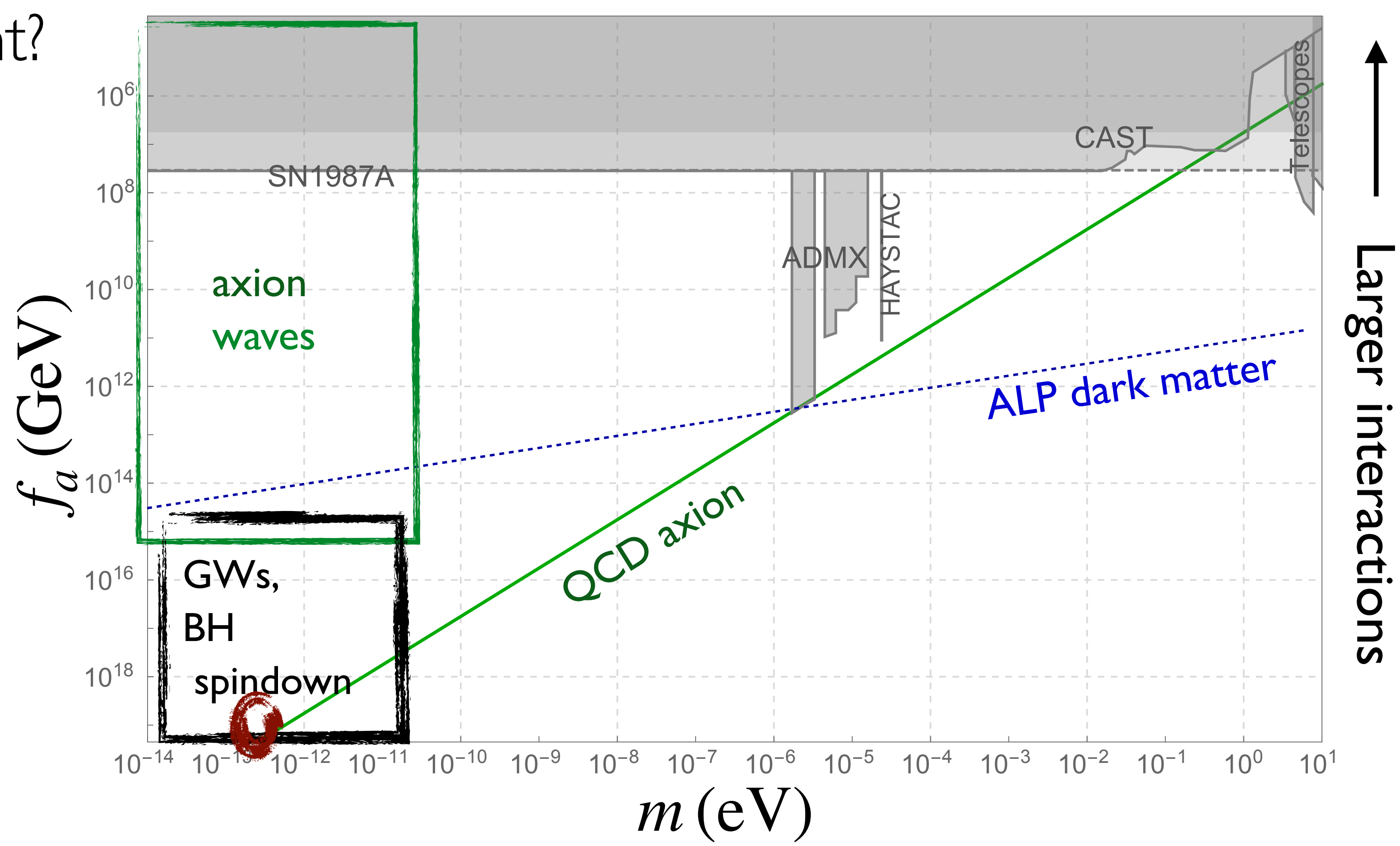
Self-Interactions



MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

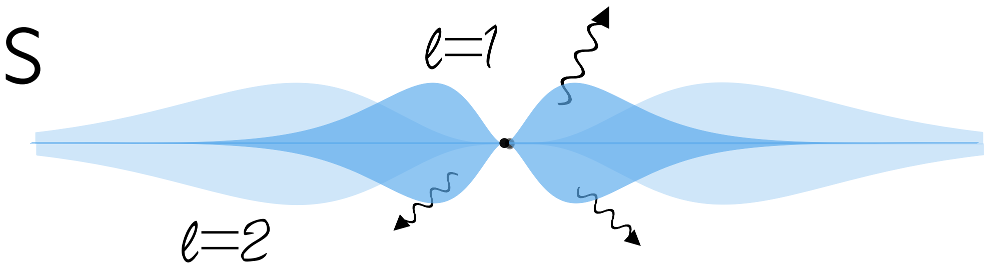
- So far, have focused on gravitational signatures of the axion
- What new effects arise when axion self-interactions become important?





Arvanitaki, Dubovsky 2010
Yoshino, Kodama 2012
Gruzinov 2016
Fukuda, Nakayama 2020

Self-Interactions



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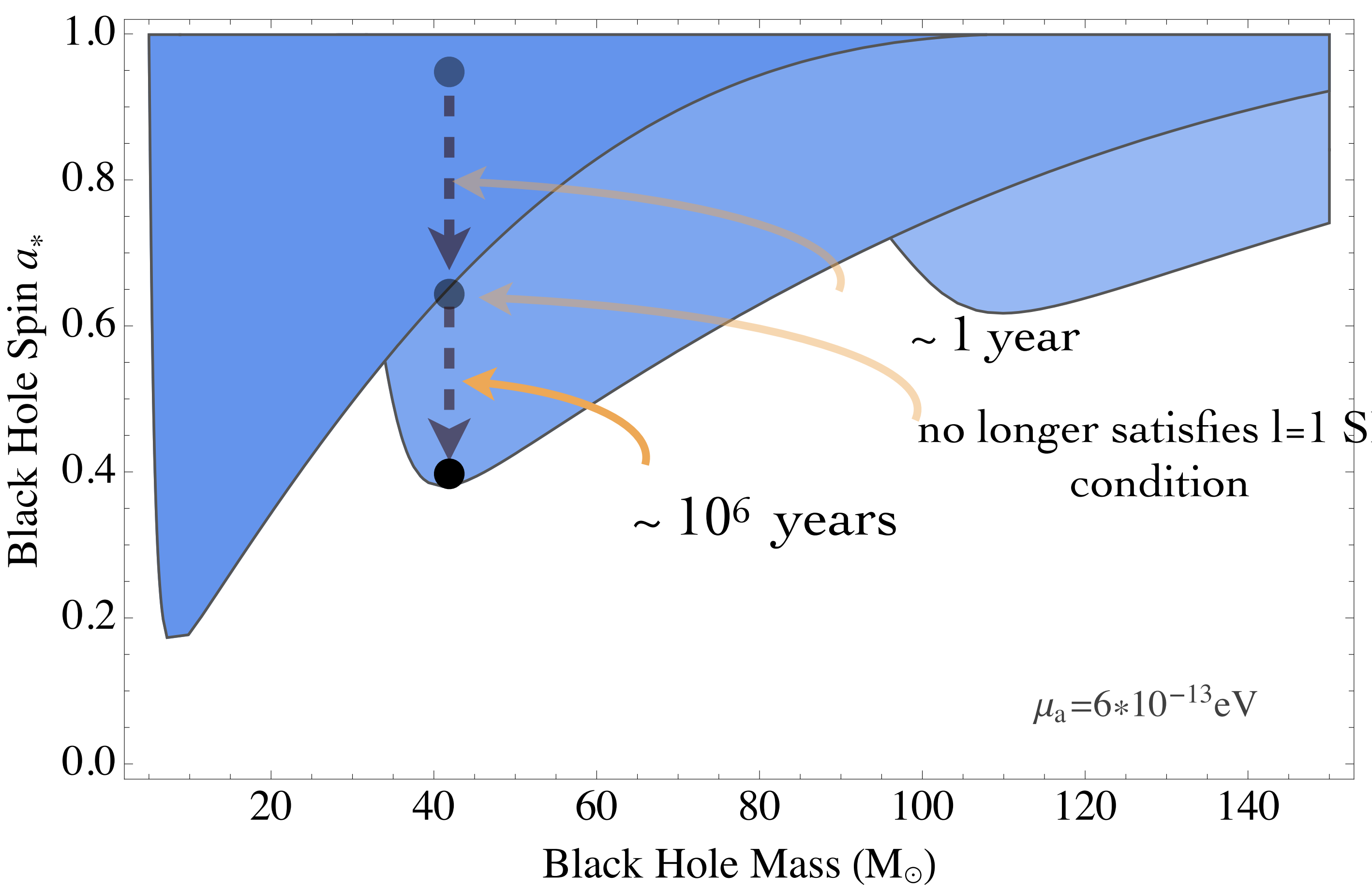
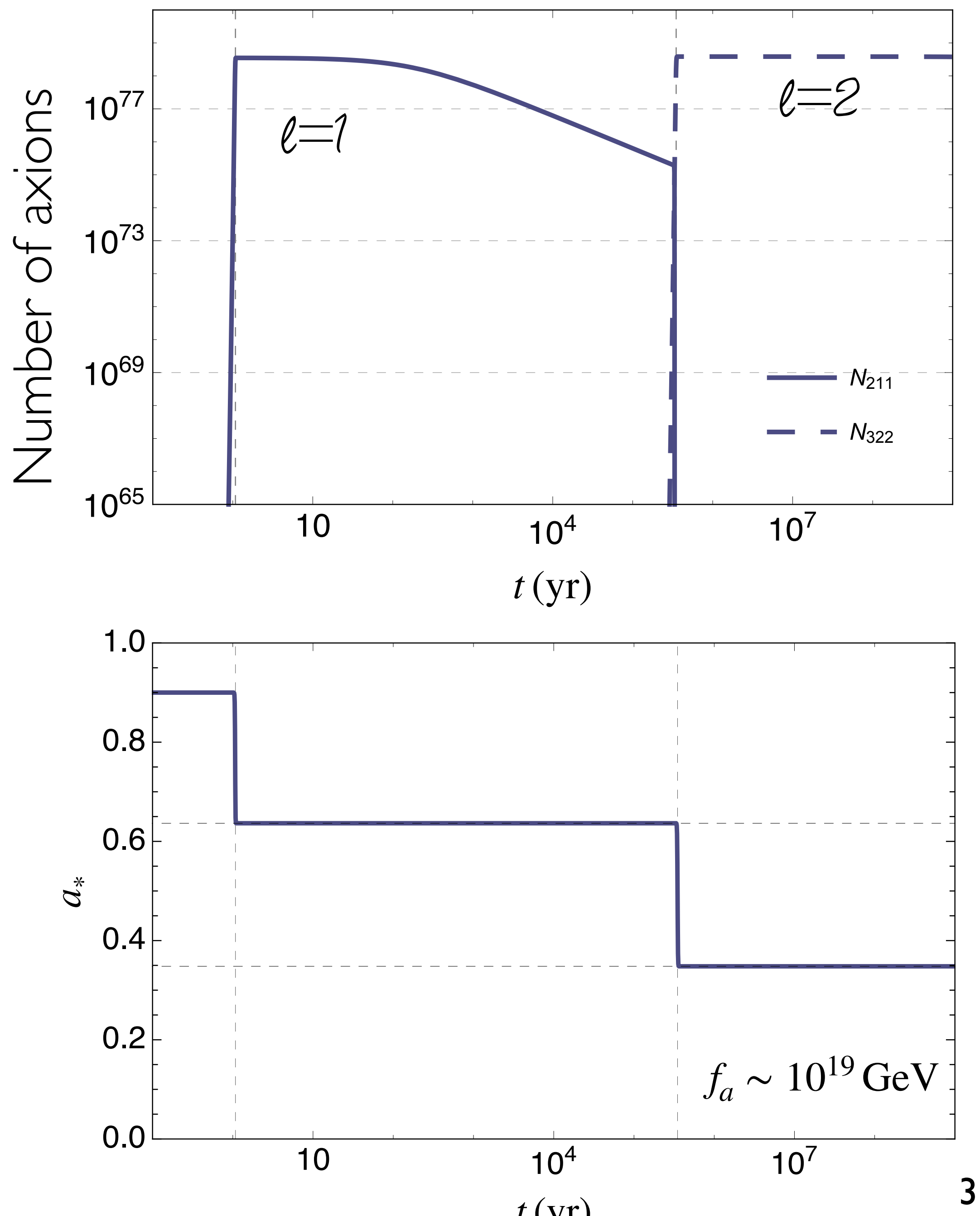
Small self-interactions: $f_a \sim M_{\rm Pl}$

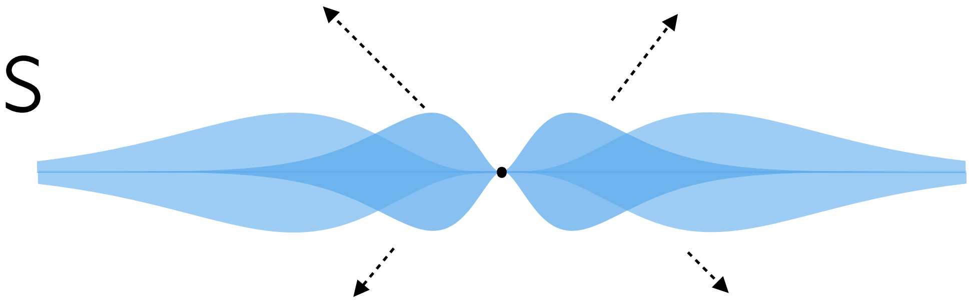
- BH spins down: next level formed; annihilations to GWs deplete first level
- Next level has a superradiance rate exceeding age of BH



Time evolution



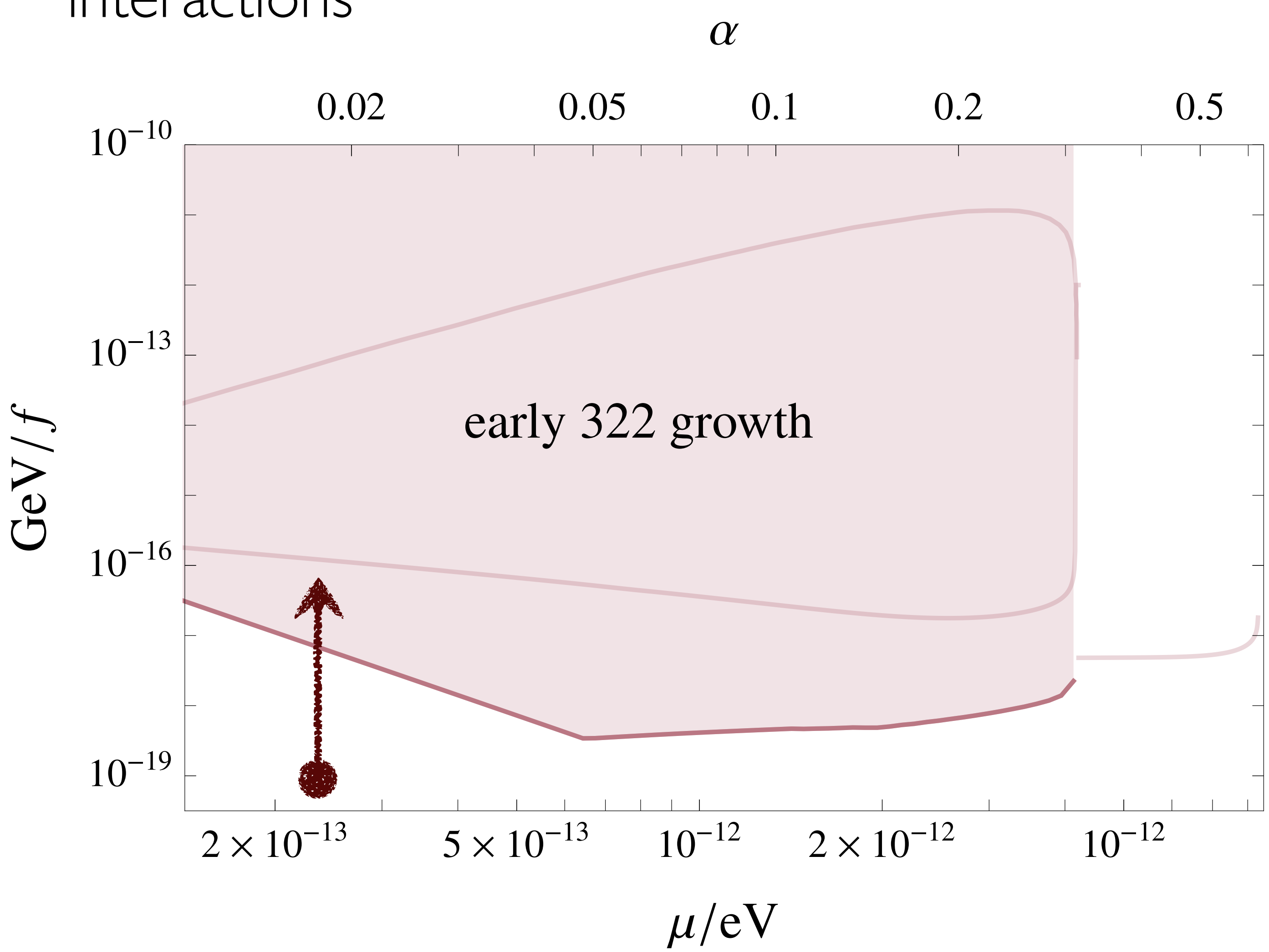
Self-Interactions



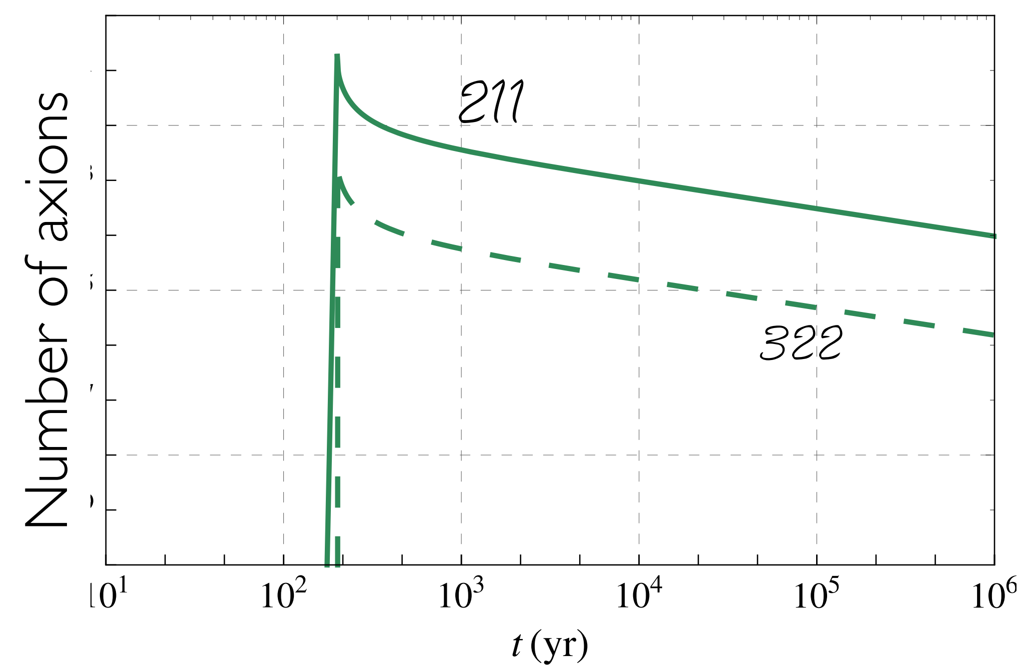
MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

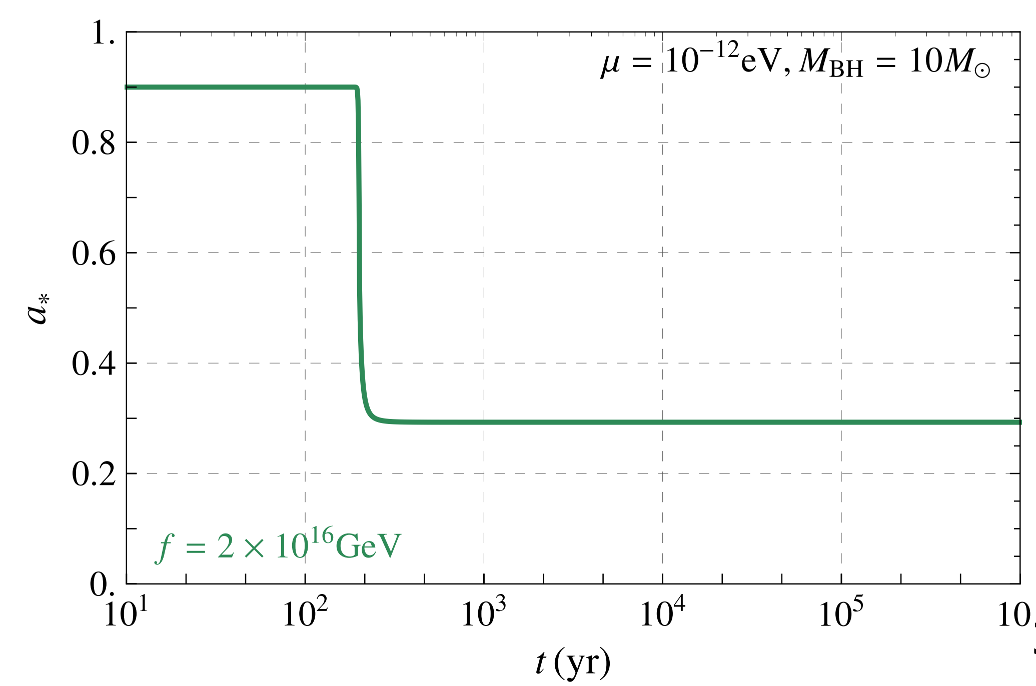
Small self-interactions:

- Black hole energy sources the first level cloud (211) through superradiance
- Second level (322) populated through self-interactions



Time evolution





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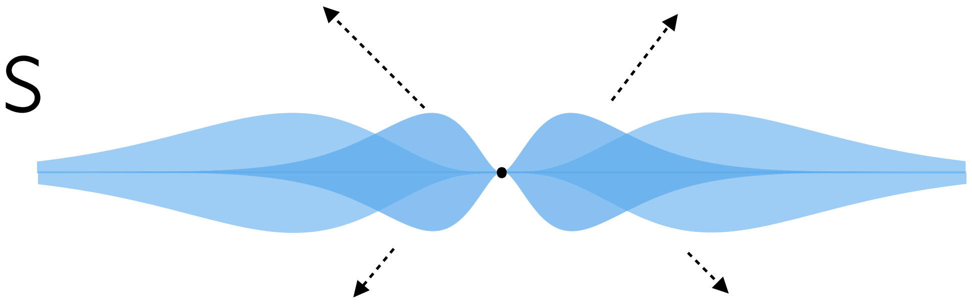
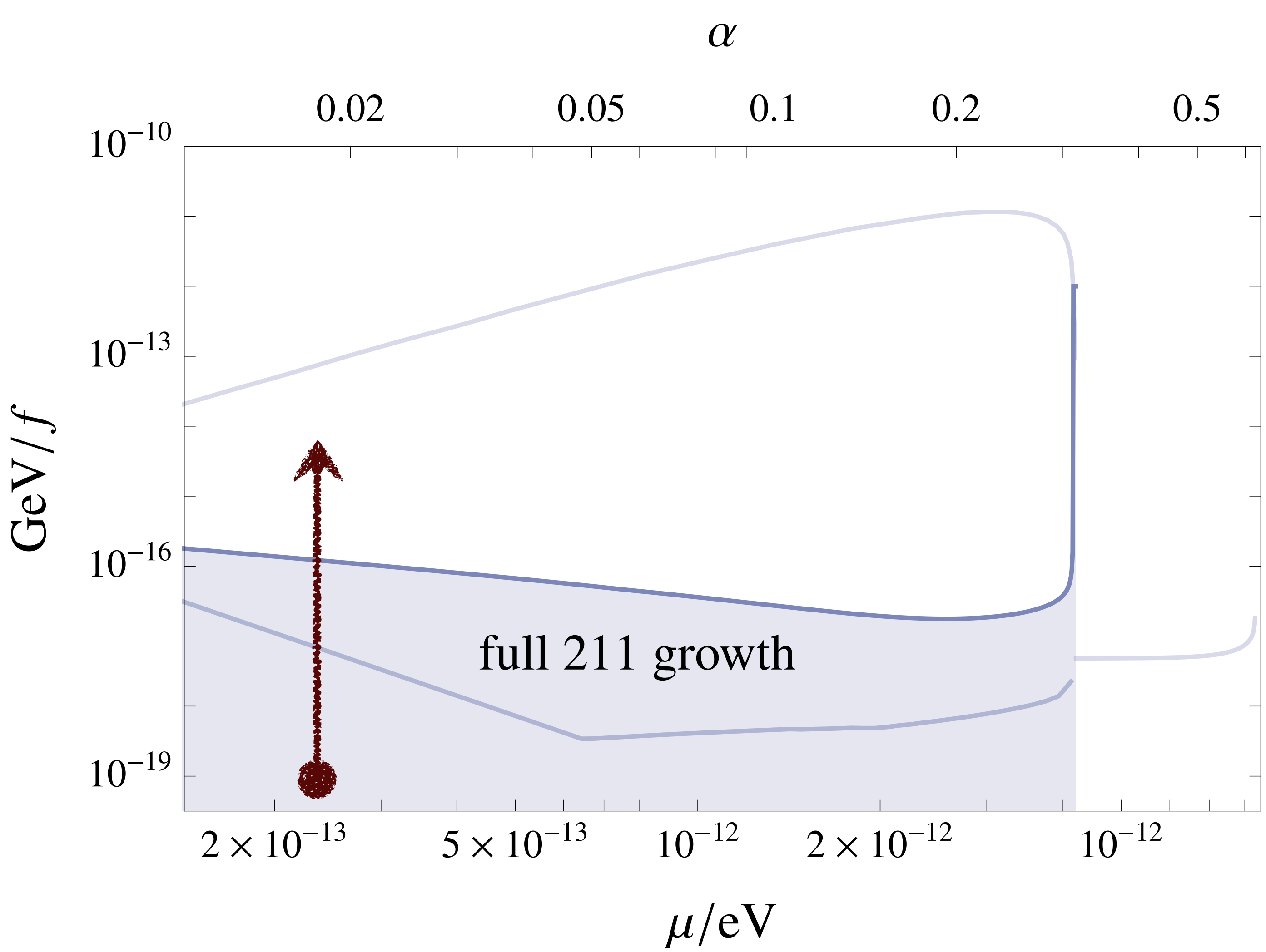
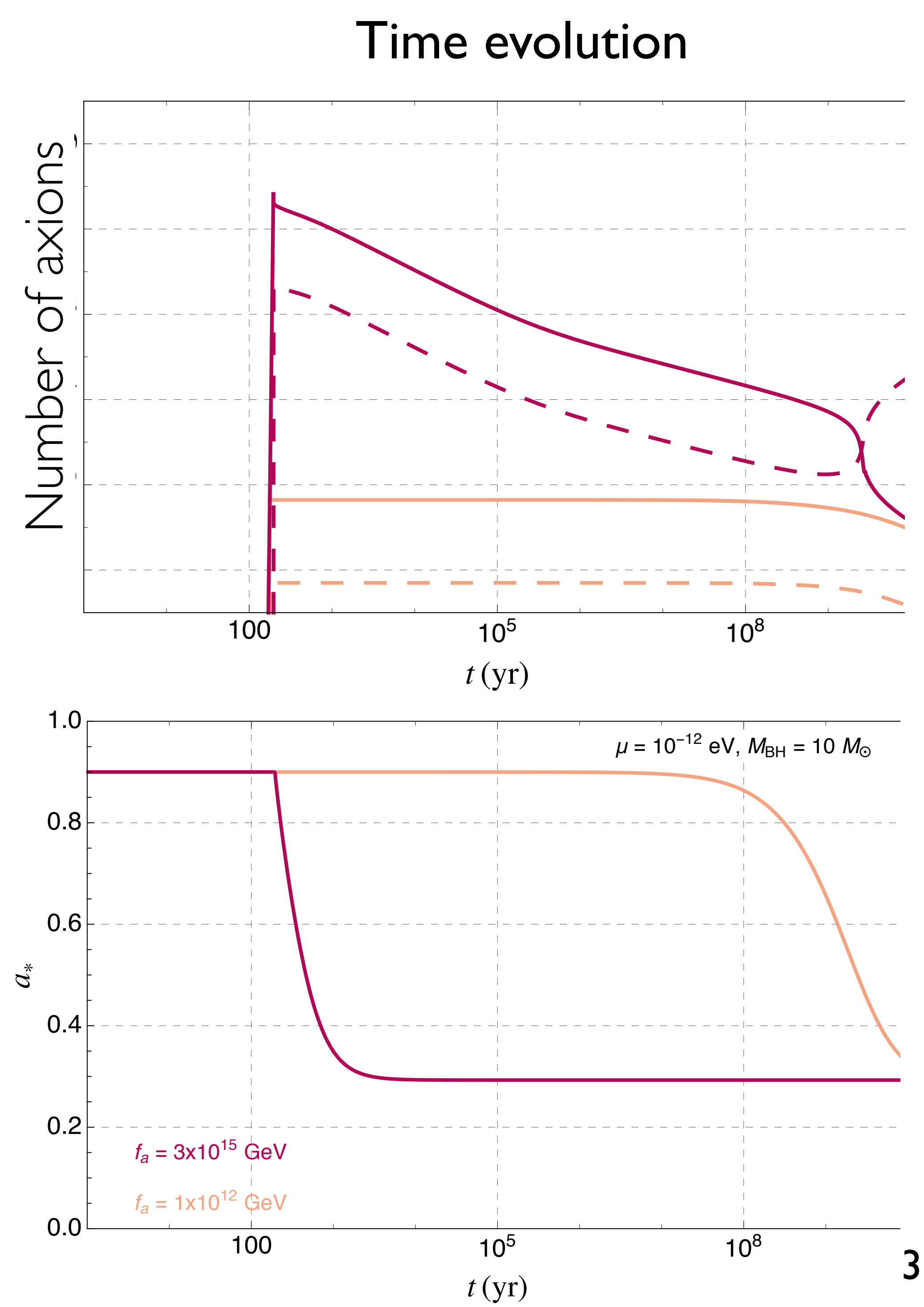


MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

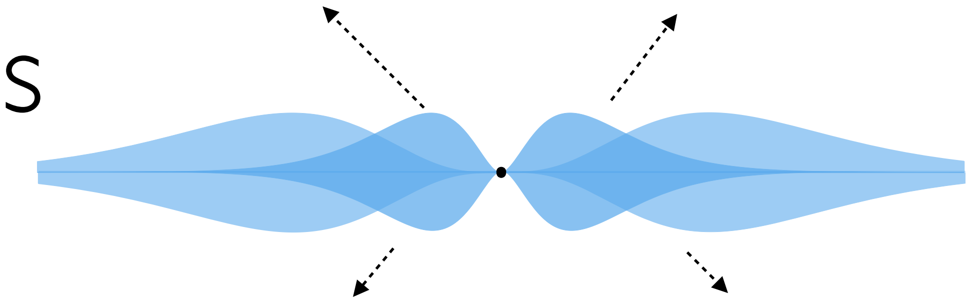
Moderate self-interactions:

- New energy loss mechanisms (into the BH and waves to infinity)
- 211 no longer grows to maximum





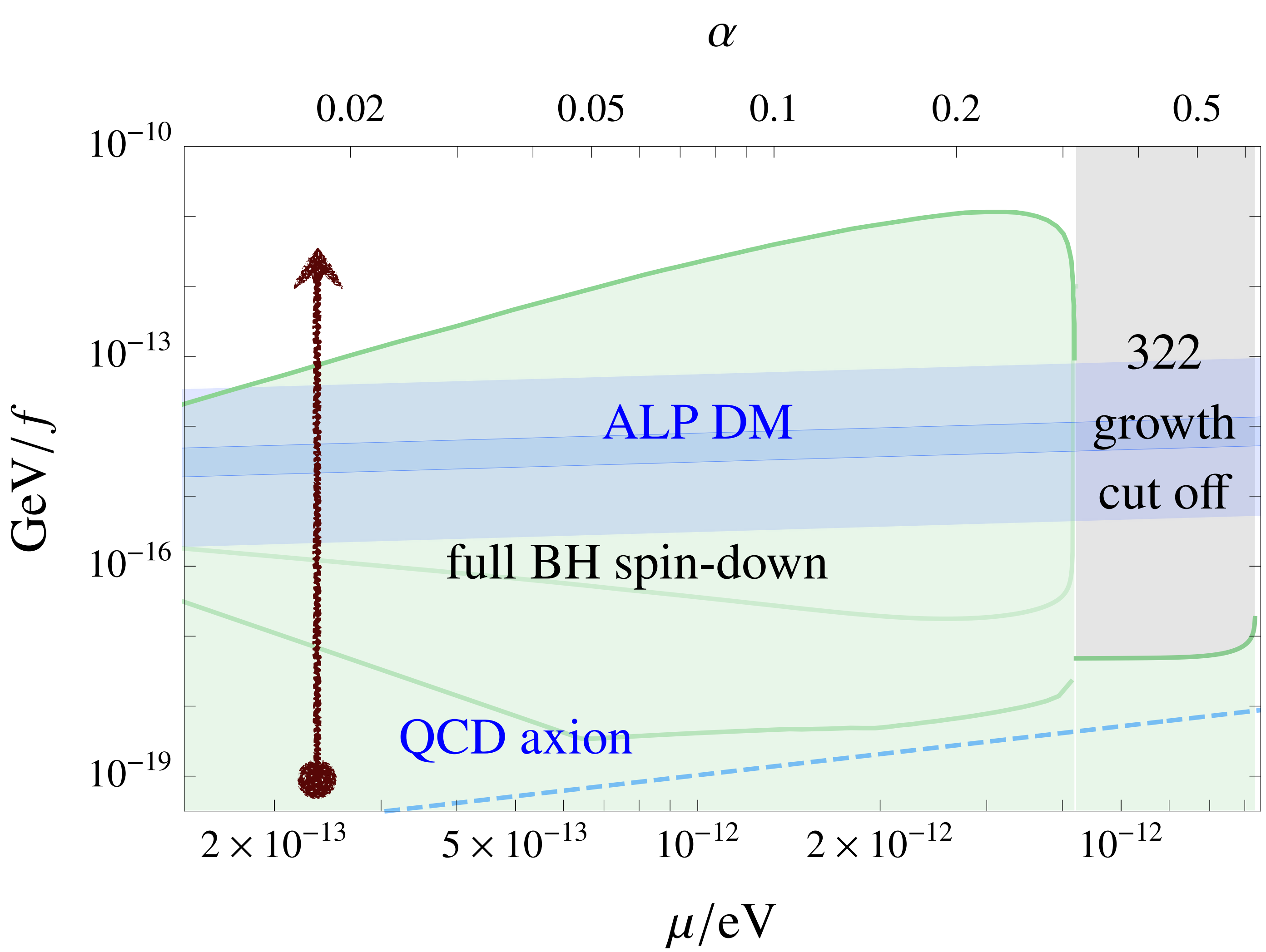
Self-Interactions



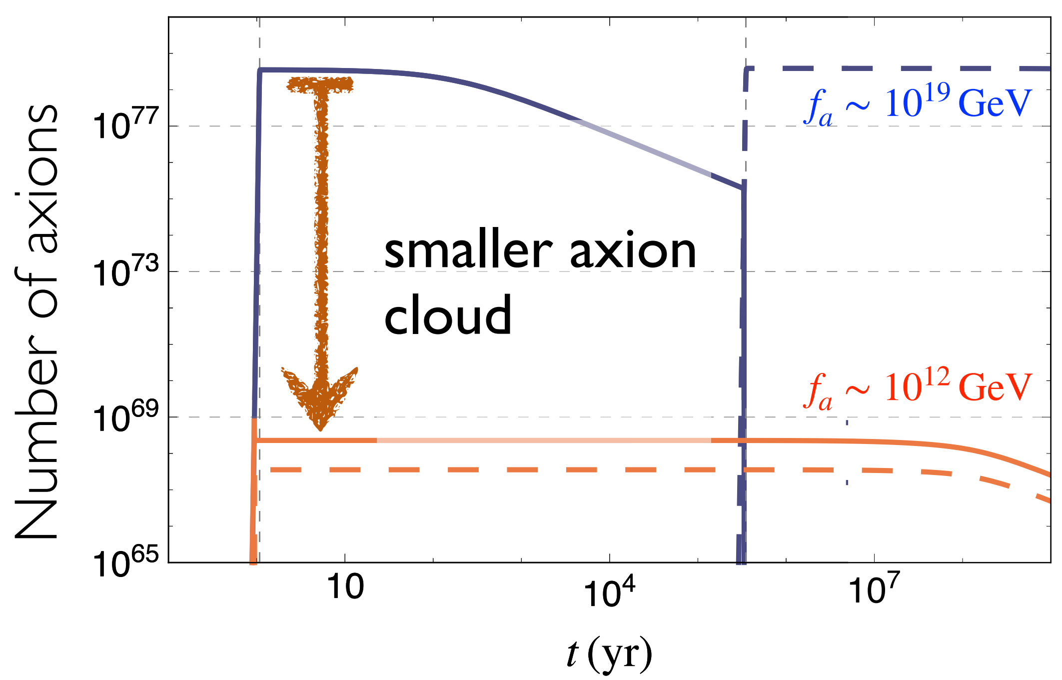
MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

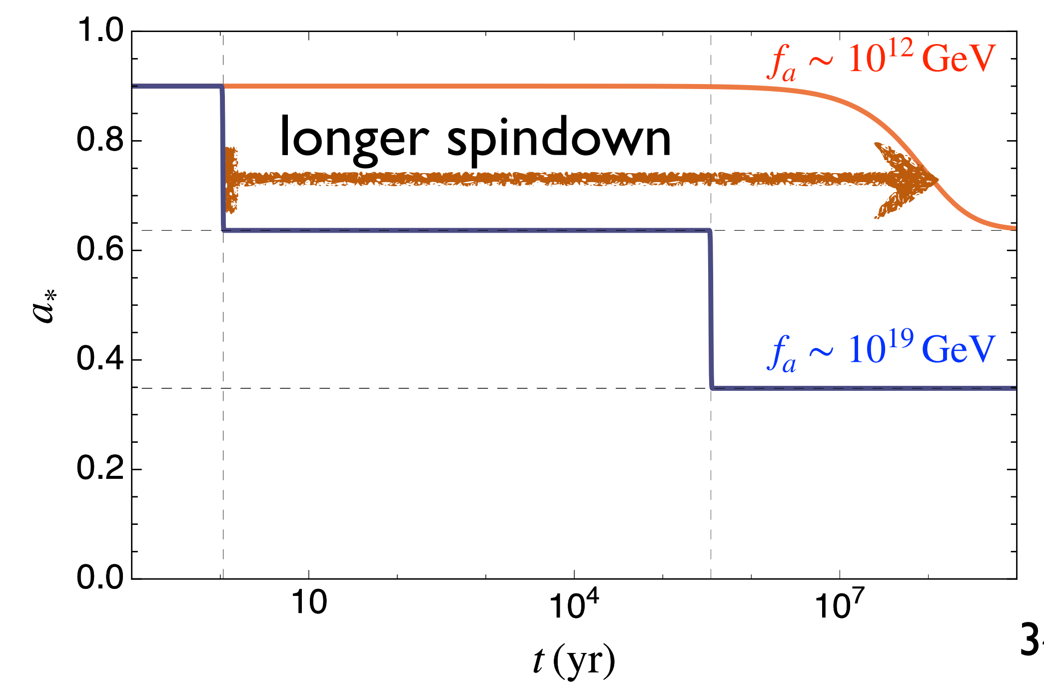
Large self-interactions:

- Smaller axion cloud parametrically slows the spindown of the black hole, equiliubrium can last longer than the age of the universe

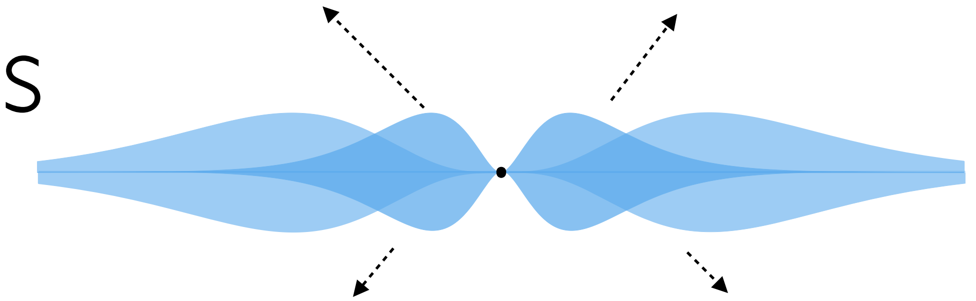


Time evolution



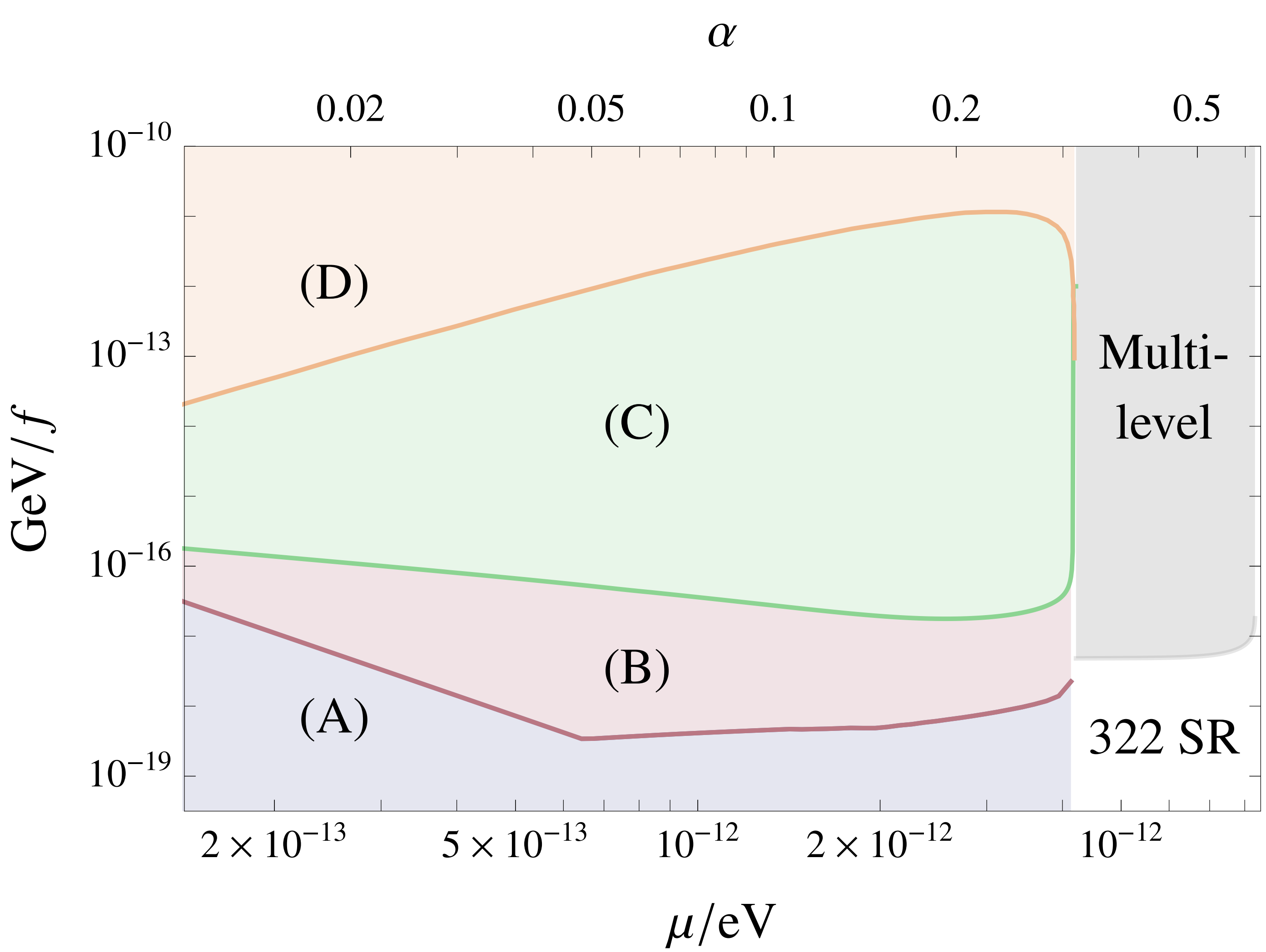


Self-Interactions



A range of dynamics for different axion self-interactions with different observational implications

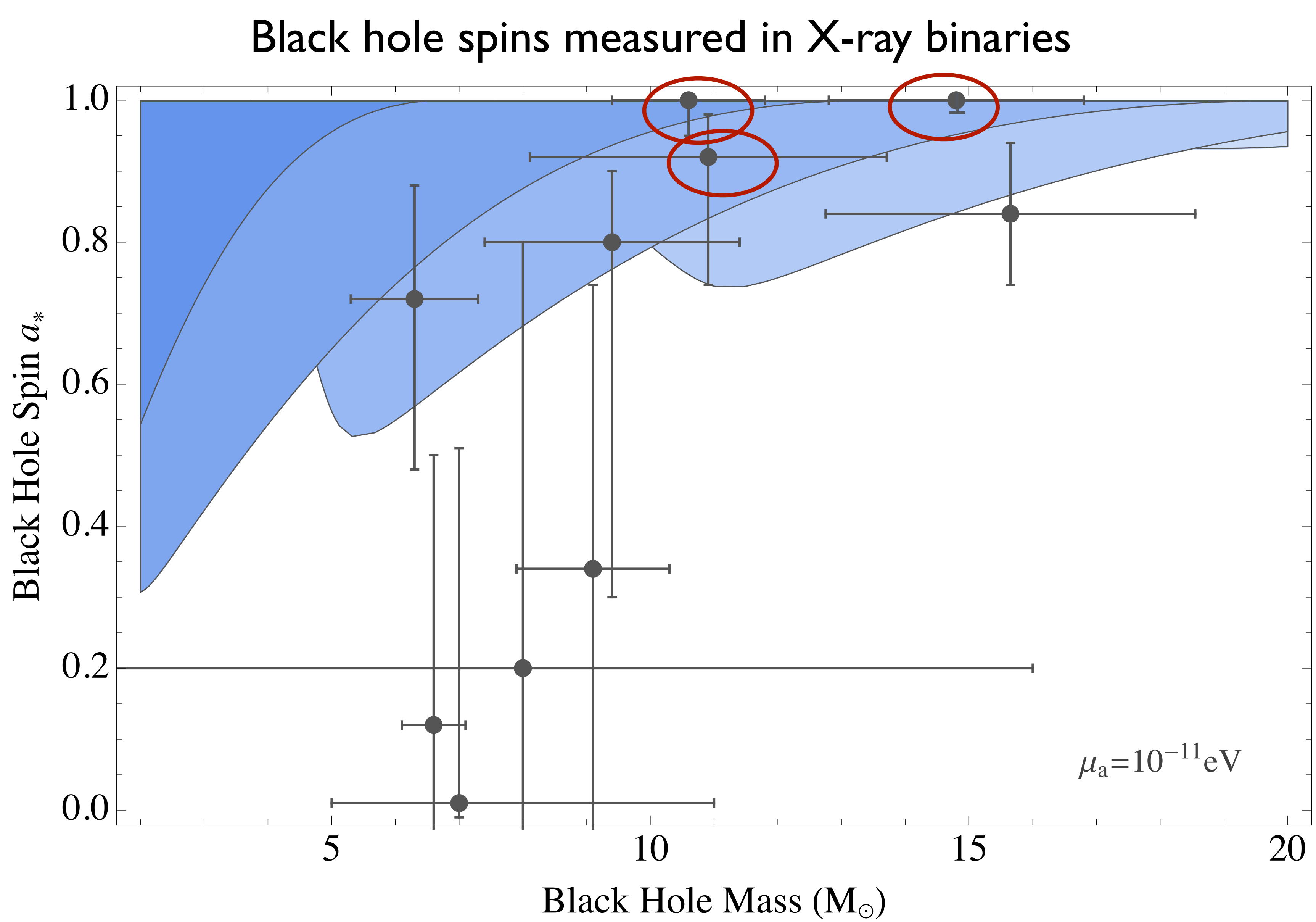
MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*



- (A): 'gravitational superradiance': gravitational waves, spindown
- (B): two level quasiequilibrium: gravitational waves, transitions, spindown
- (C): reduced occupation numbers: small amplitude gravitational waves, spindown, axion waves
- (D): no spindown, axion wave emission

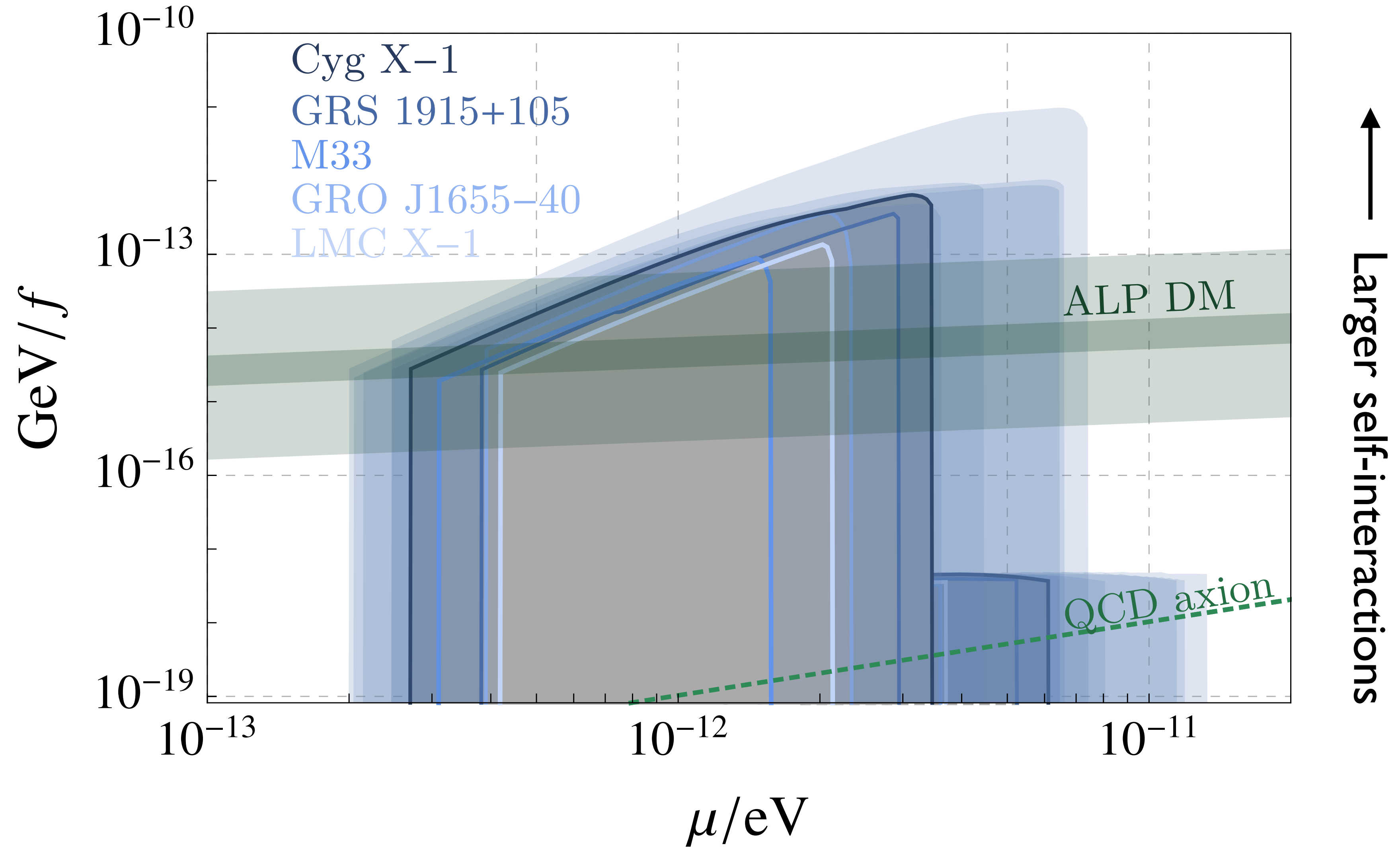
Black Hole Spins

Black hole spin and mass measurements can be used to constrain axion parameter space



Black Hole Spins

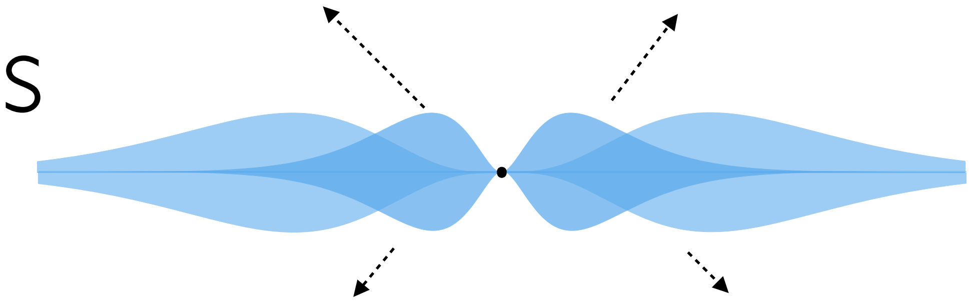
Five currently measured black holes combine to set limit:



MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

- As self-interactions increase, the number of axions in each level is bounded and spin extraction from the black hole slows

Self-Interactions

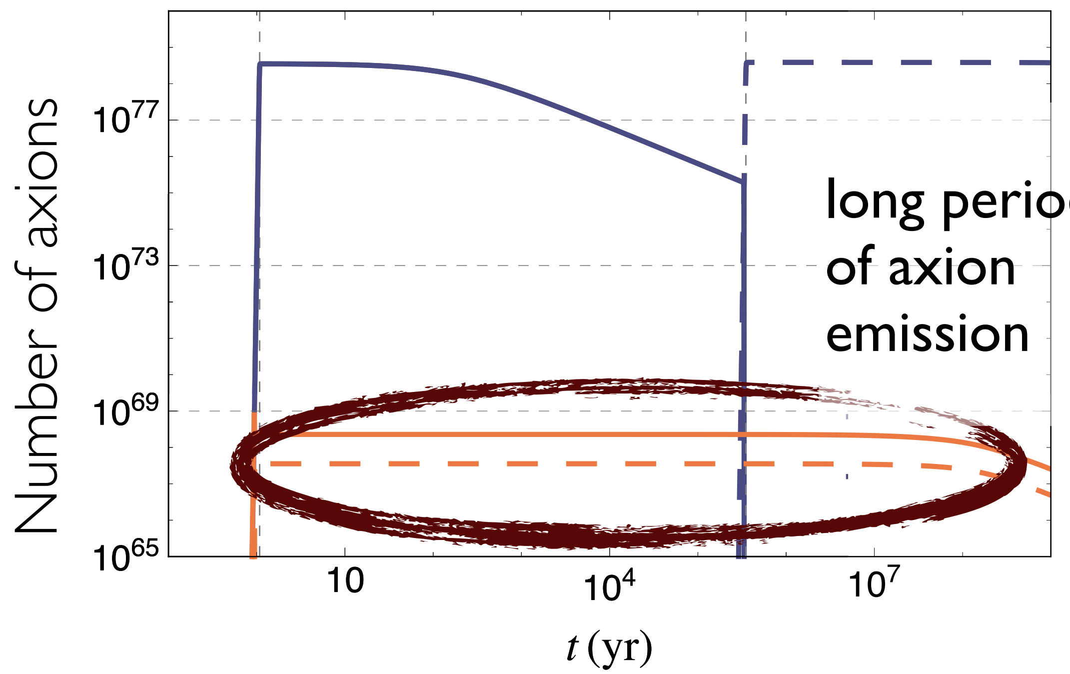


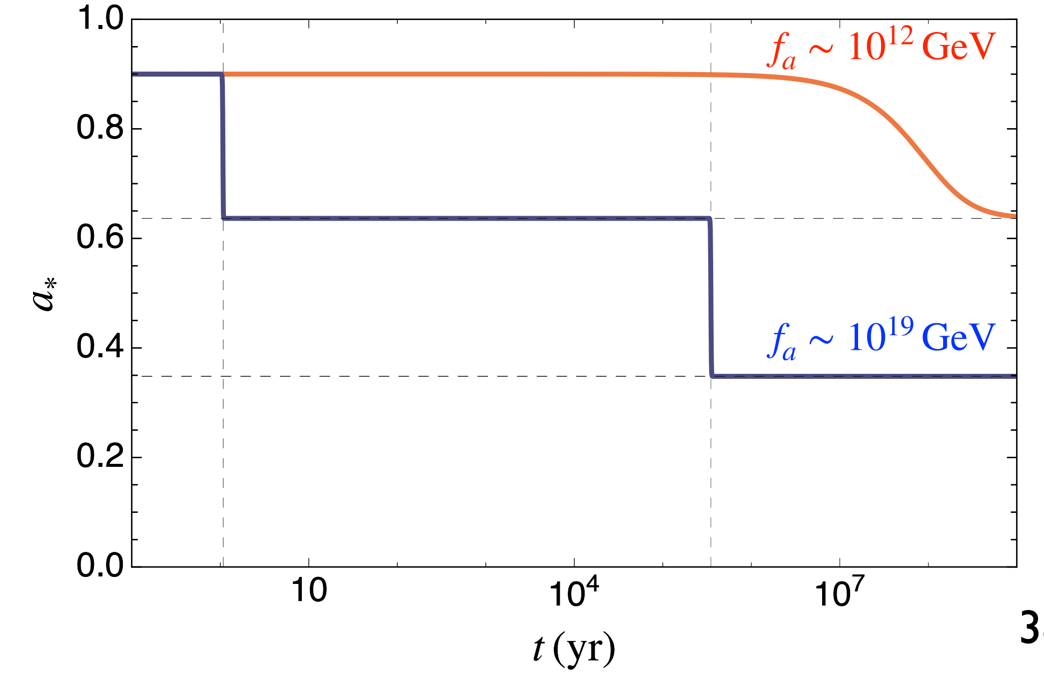
MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

Larger self-interactions: $f_a \sim 10^{12}\text{GeV}$

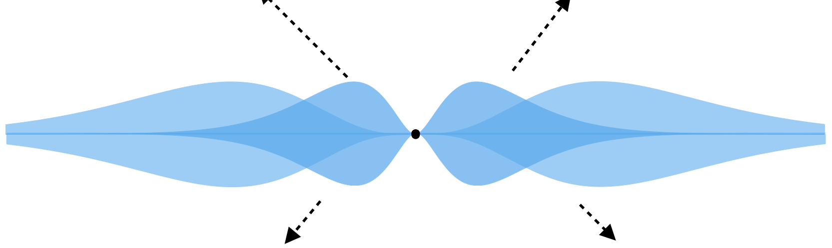
- Black hole energy slowly gets converted to axions
- Cloud size constant over time; not large enough to affect the black hole evolution
- Non relativistic coherent axion waves emitted at constant amplitude throughout black hole lifetime

Time evolution





Axionic Beacons

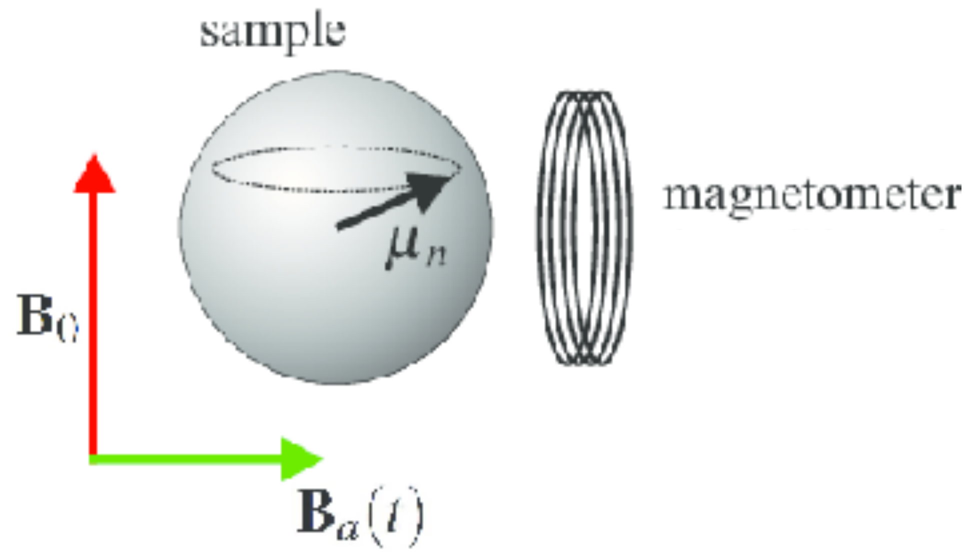


A new source of axions in the universe

- Black hole energy slowly and constantly converted to axion waves
- Can be detected directly if axions couple to the Standard Model
- Fractional field amplitude independent of self interactions, comparable to laboratory search targets

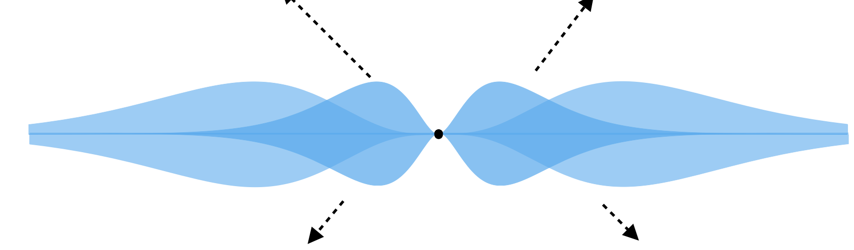
$$\frac{a}{f_a} \sim 10^{-17}\left(\frac{10^{-12}\mathrm{eV}}{\mu}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{\mathrm{kpc}}{r}\right)$$

- Axion field gradient acts like a magnetic field on particle spins



CASPEr Budker, Graham, Ledbetter, Rajendran, Sushkov (2014)
Kimball et al (2017)

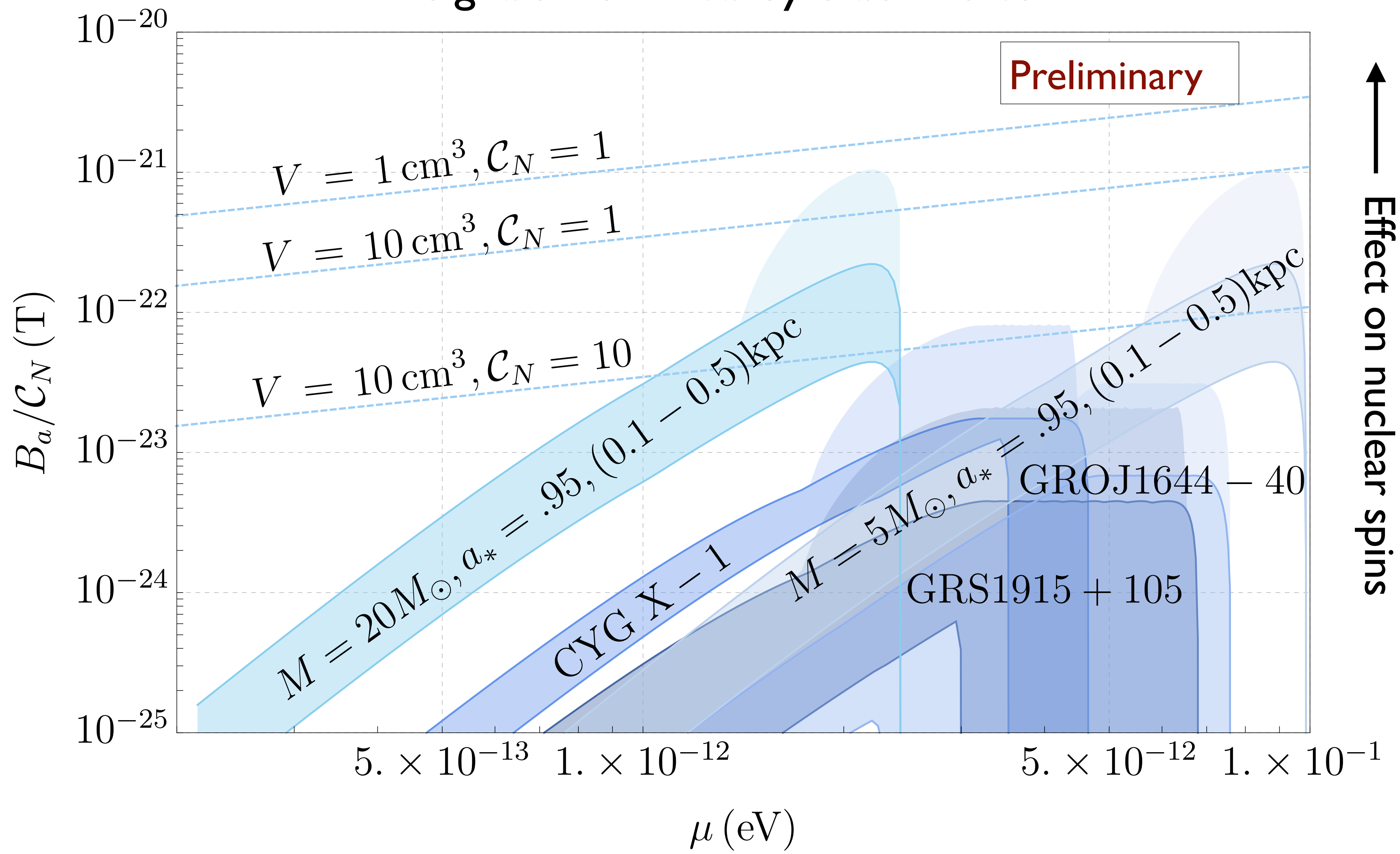
Axionic Beacons



Black hole energy constantly converted to axion waves

- Signal strength ***constant in time***, independent of self interaction strength at small *fa*
- Axion waves observable in axion force/dark matter experiments (ARIADNE, CASPER…)
- Requires different data analysis strategies (*c.f.* LIGO continuous waves search)

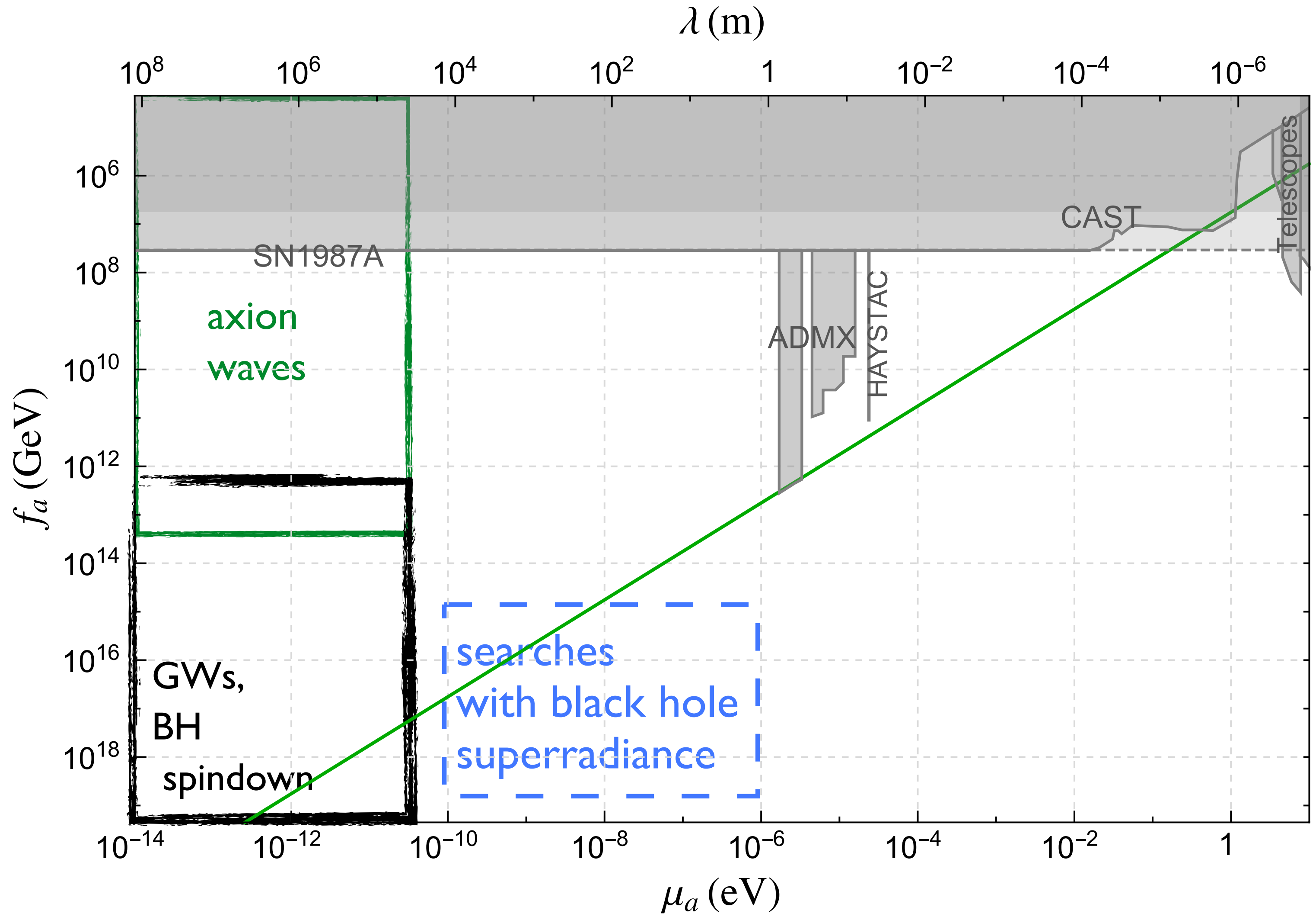
Signals from nearby black holes

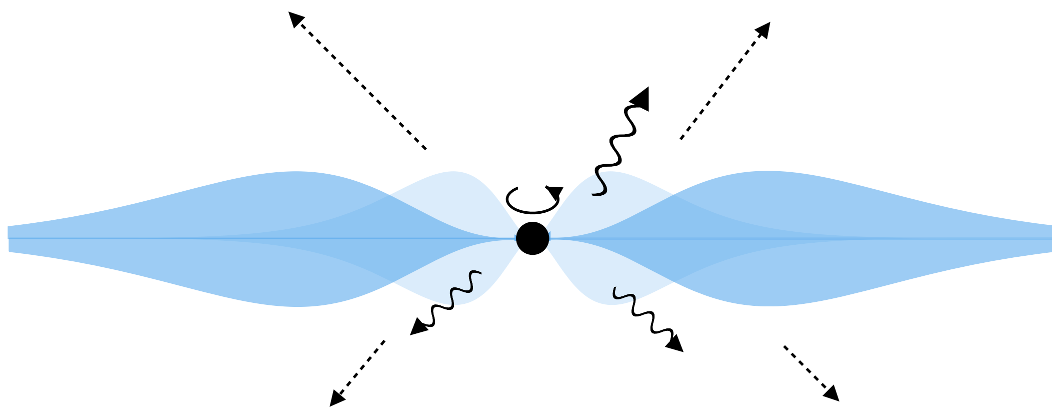


MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

Gravitational Atoms and Axionic Beacons

- In the presence of ultralight axions, black holes spin down, converting their energy to axion clouds
- Axion clouds produce monochromatic wave radiation; we are looking for these signals in LIGO data
- Self-interactions of axions slow down energy extraction from black holes and populate the universe with axion waves





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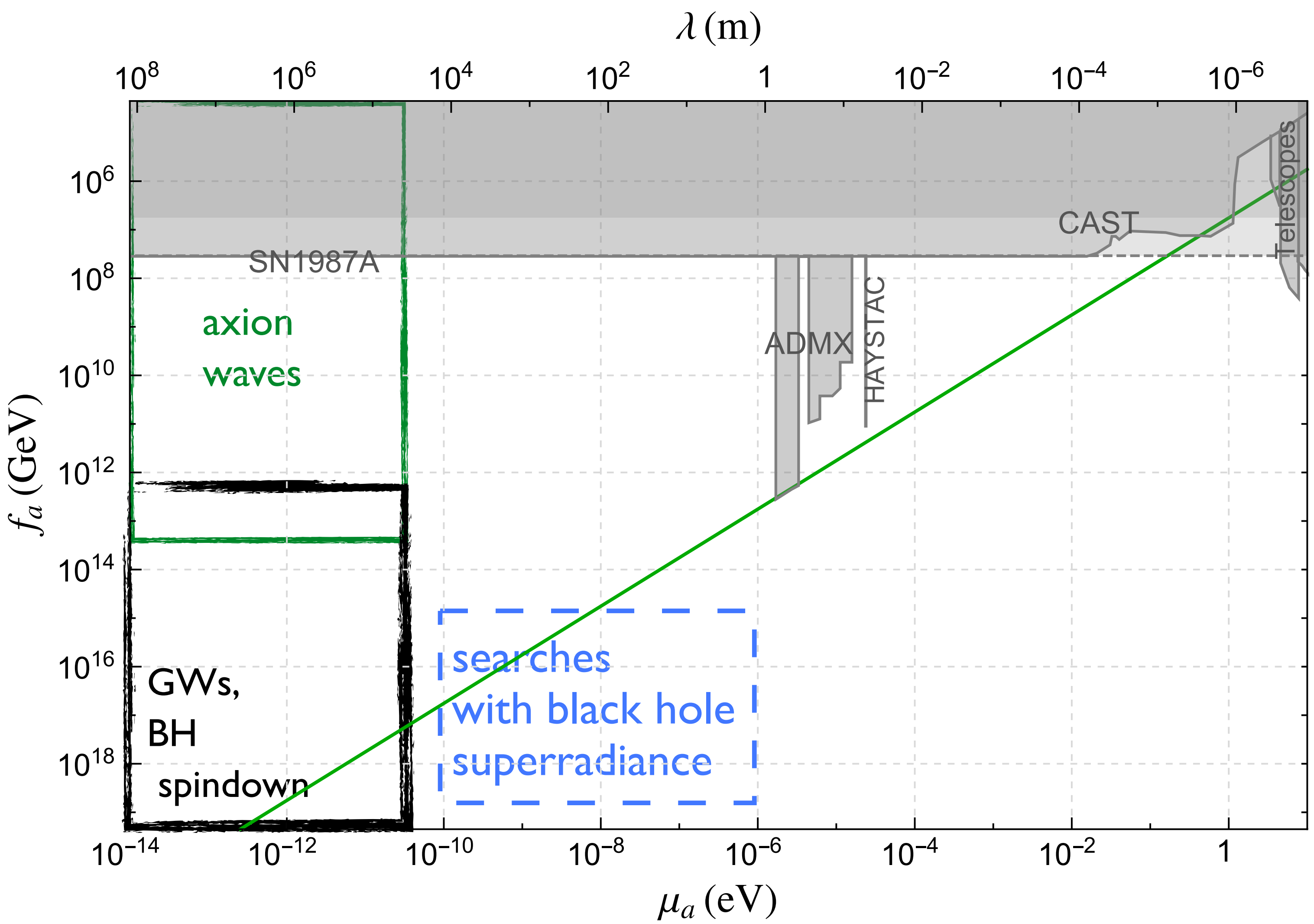
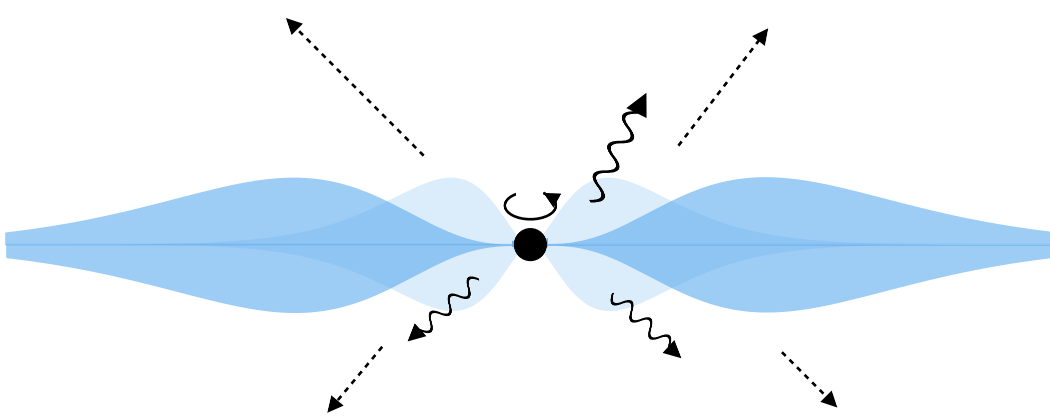




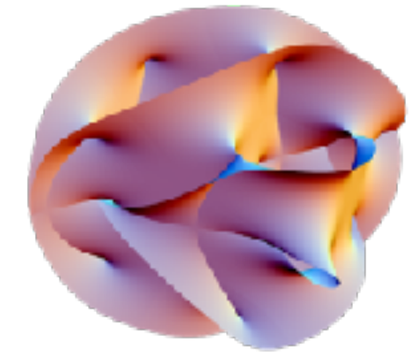
Questions ?

?

?

Theory

The QCD axion
in string theory



- 4D axions appear as zero modes of gauge fields compactified in extra dimensions

- Nonperturbative gravity effects generate a mass, exponentially suppressed:

$$\mu^4 e^{-S}\left(1-\cos\left(\frac{\phi}{f}\right)\right)$$

- Requiring string theory to produce the QCD axion puts an upper bound on the size of these corrections

$$\mu^4 e^{-S} \ll \Lambda^4$$

- Complex string compactifications produce multiplicity of light string axions

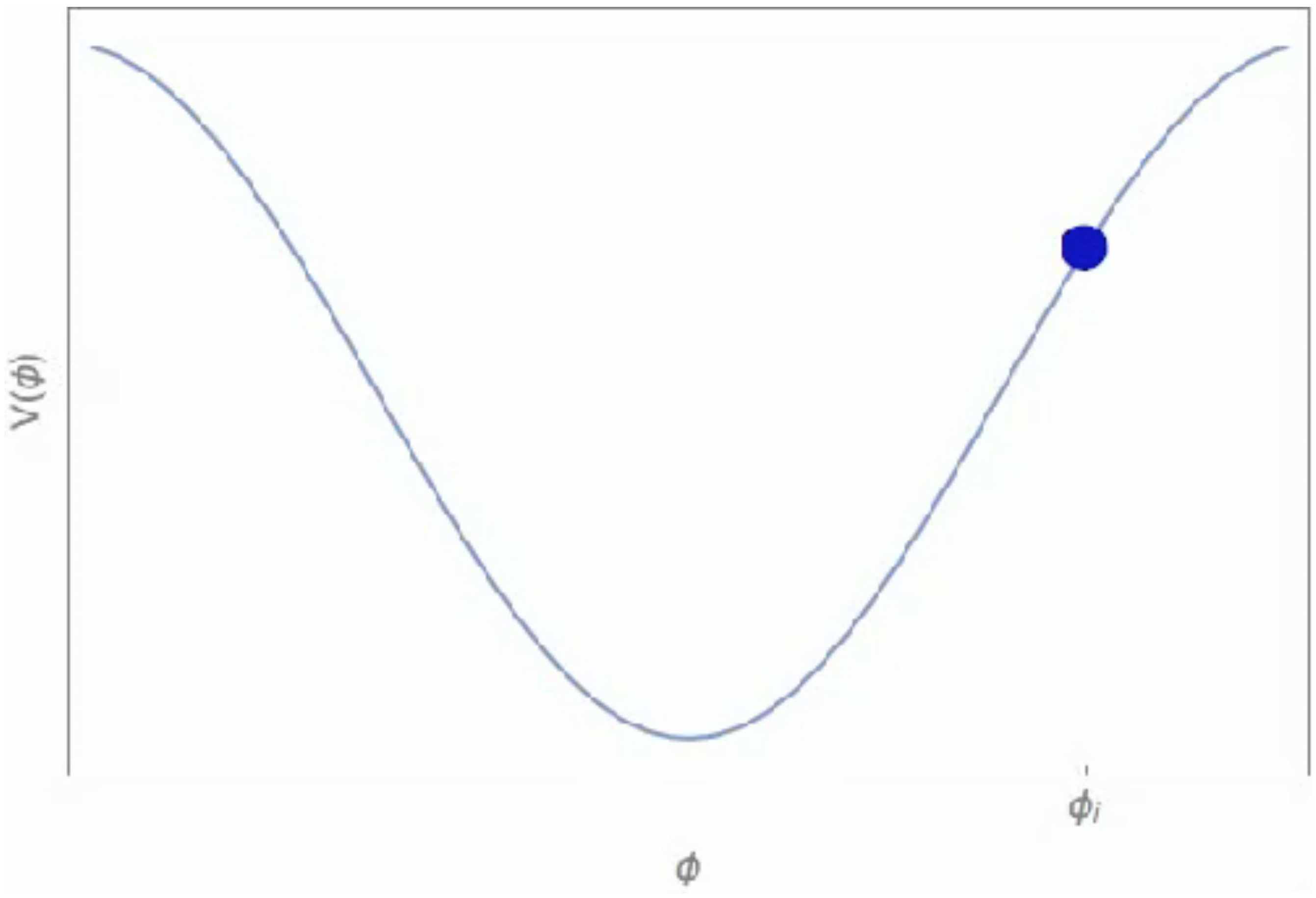
Kallosh, Linde, Linde, Susskind [9502069]
Svrcek , Witten [0605206]
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell [0905.4720]

Axion dark matter

- Cosmological evolution analogous to damped harmonic oscillator with frequency given by the mass and damping by Hubble friction:

$$\ddot{a} + 3H\dot{a} + m^2 a = 0$$

- Early on, H >> m: frozen by Hubble friction
- When H < m: begins to oscillate; energy density dilutes as nonrelativistic matter



Predict DM density as a function of *m*, *f*:

$$\frac{\rho_{\rm a}}{\rho_{\rm cdm}} \sim \left(\frac{m}{\rm eV}\right)^{1/2} \left(\frac{f}{10^{11}{\rm GeV}}\right)^2 \left(\frac{a_i}{f}\right)^2$$

QCD axion

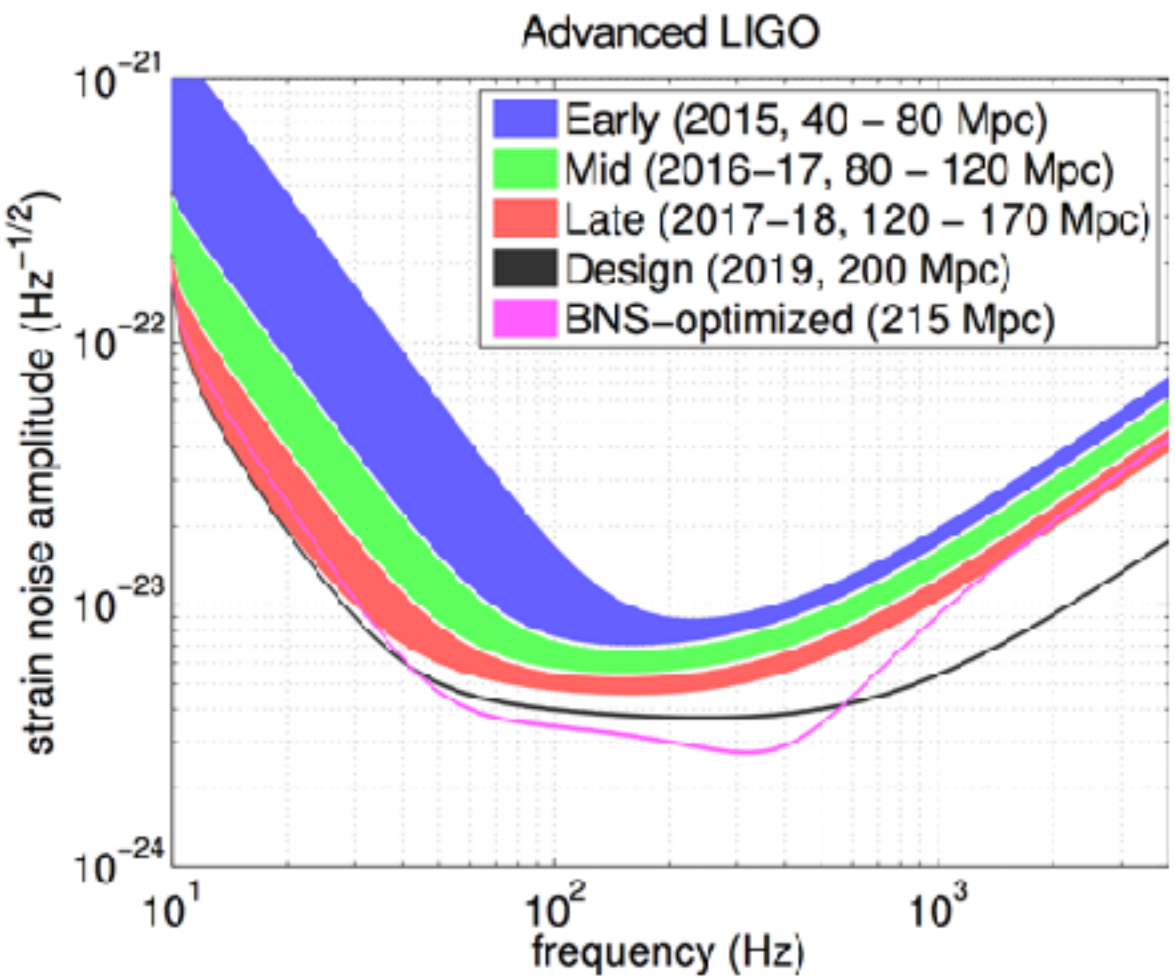
$$\frac{\rho_{\rm a,QCD}}{\rho_{\rm cdm}} \sim \left(\frac{f}{{\rm few} \times 10^{11}{\rm GeV}}\right)^{7/6} \left(\frac{a_i}{f}\right)^2$$

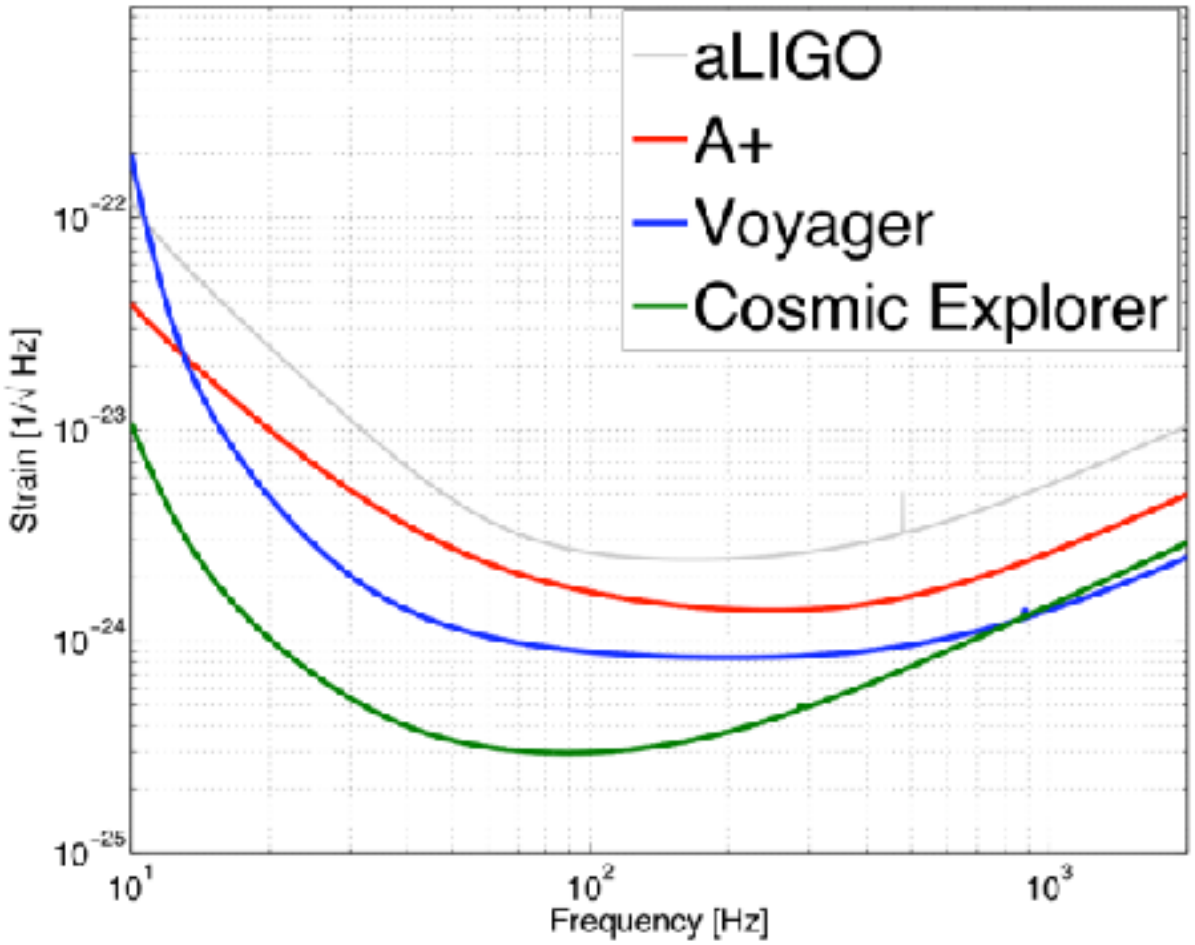
Preskill, Wise, Wilczek (1983)
...

Gravitational Wave signatures

Gravitational Wave Signals

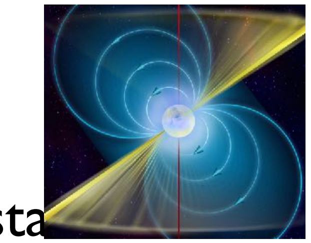
Advanced LIGO sensitivity





- Fits into searches for long, continuous, monochromatic gravitational waves
- Currently looking for "mountains" on neutron stars

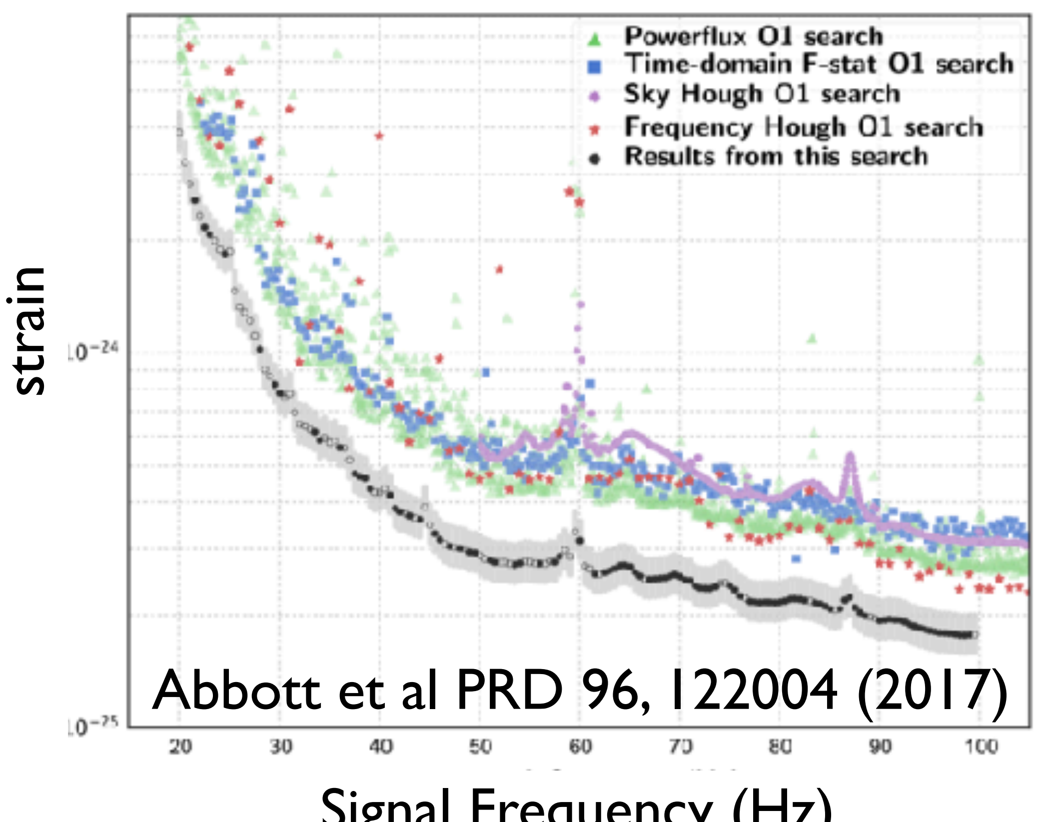
Continuous Wave Searches



Current searches for gravitational waves from asymmetric rotating neutron sta

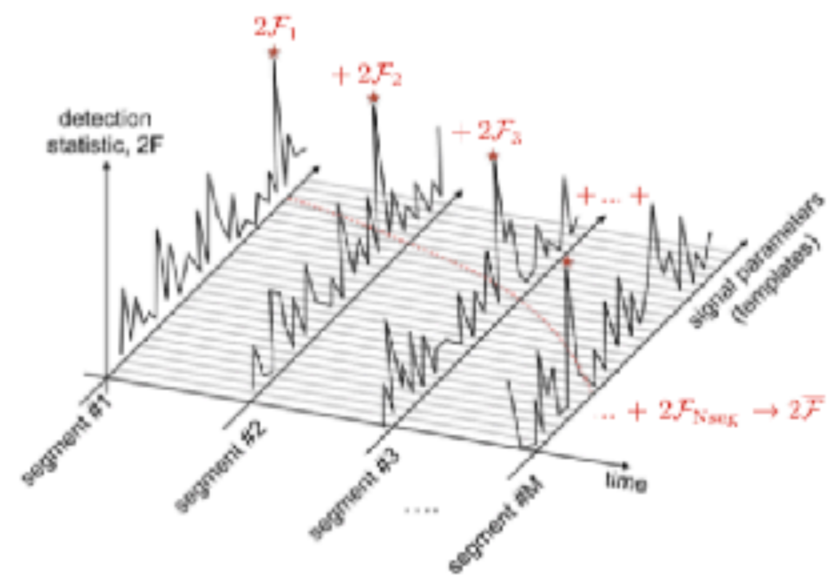
- Weak signals require long coherent integration time

All-Sky O1 Upper Limits



Abbott et al PRD 96, 122004 (2017)

e.g.,



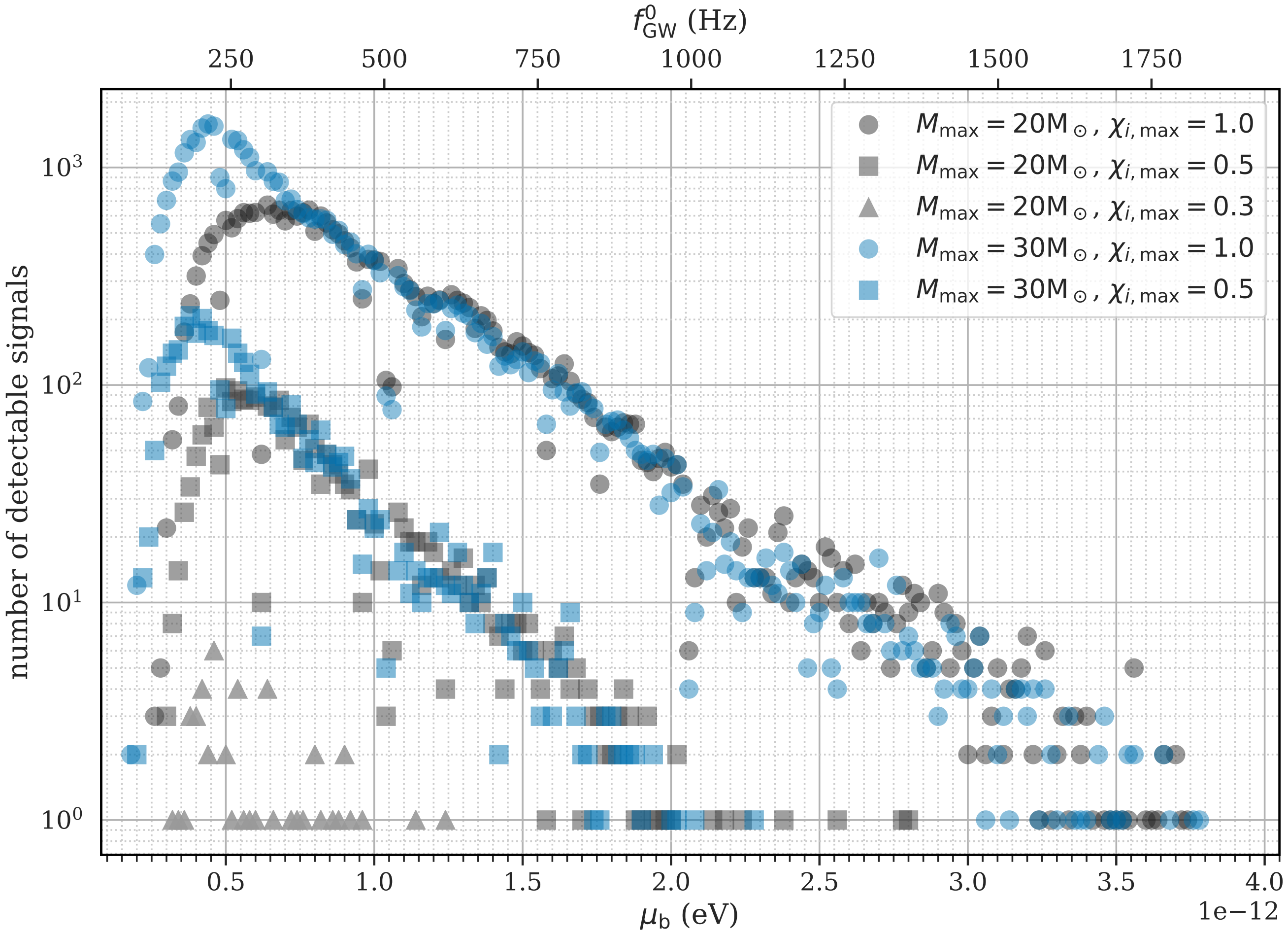
Sylvia Zhu, 2019

all-sky search
minimal assumptions

$N \sim T_{coh}^6 \sim 10^{17}$

Gravitational Wave Signals

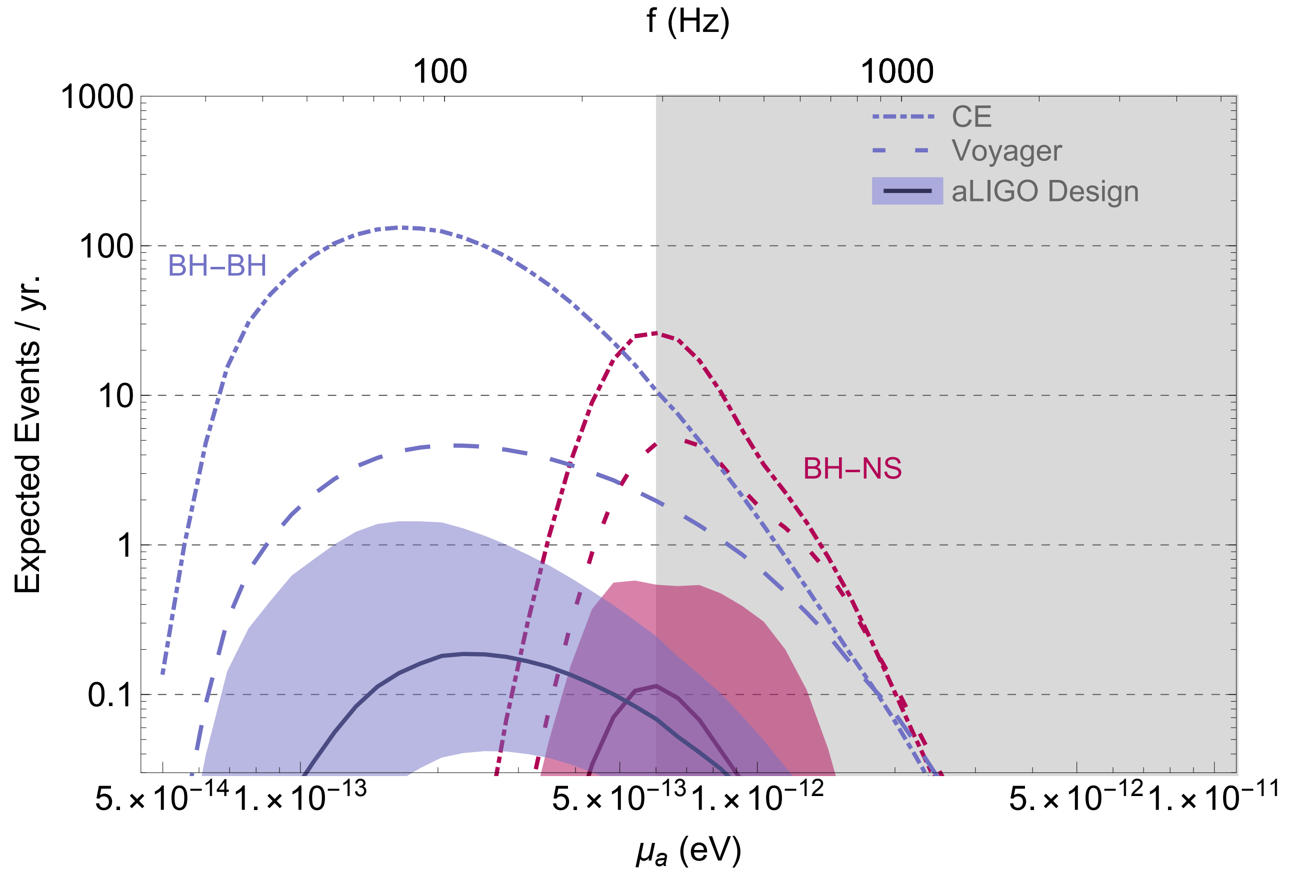
Current searches:



A. Arvanitaki, **MB**, X. Huang (2015)

- **Weak, long signals** last for ~ million years, visible from our galaxy
- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- Large density of signal per search frequency bin can degrade existing search efficiency

Future observatories:



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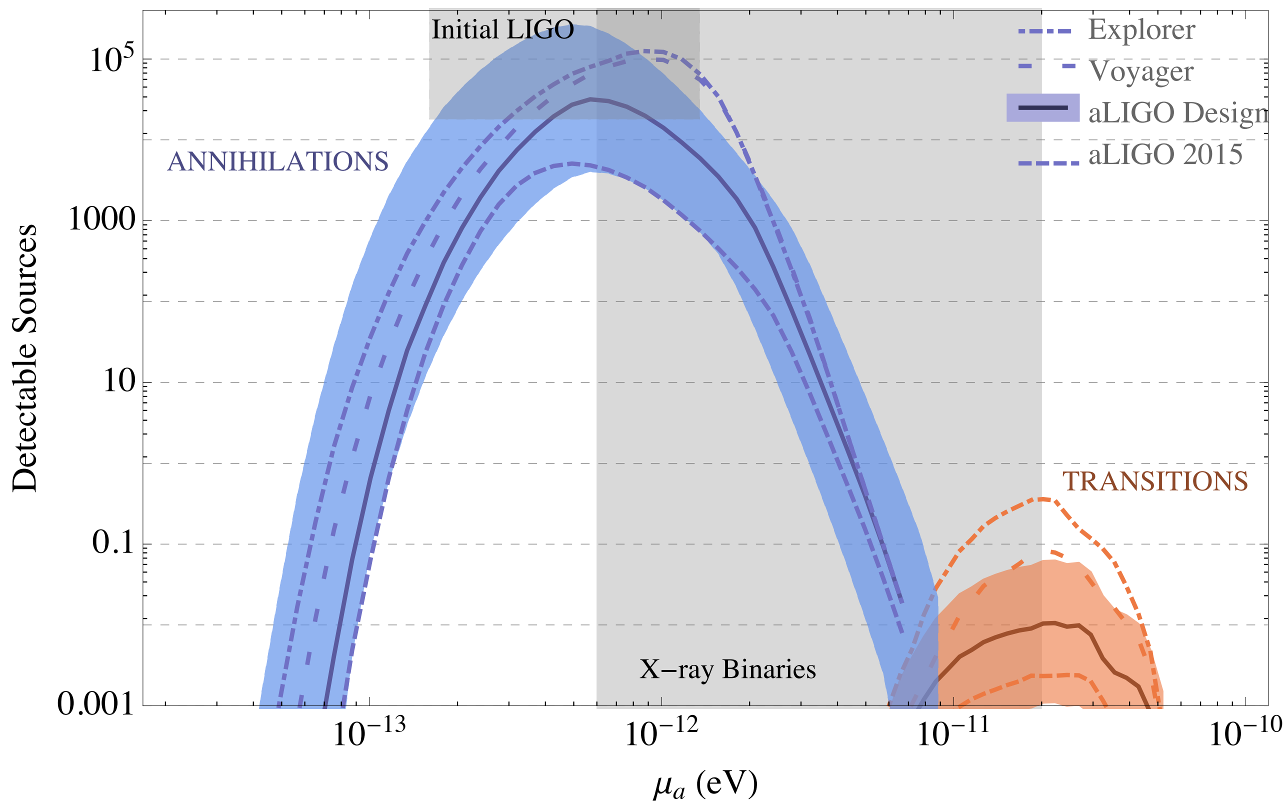
- **Short, bright signals** — directed follow-up searches to BHs in mergers
- Measure BH mass, spin, and particle mass: fully study gravitational atom
- Promising at future GW observatories, methods investigations ongoing
  - M. Isi, L. Sun, R. Brito, A. Melatos (2019)

Gravitational Wave Signals



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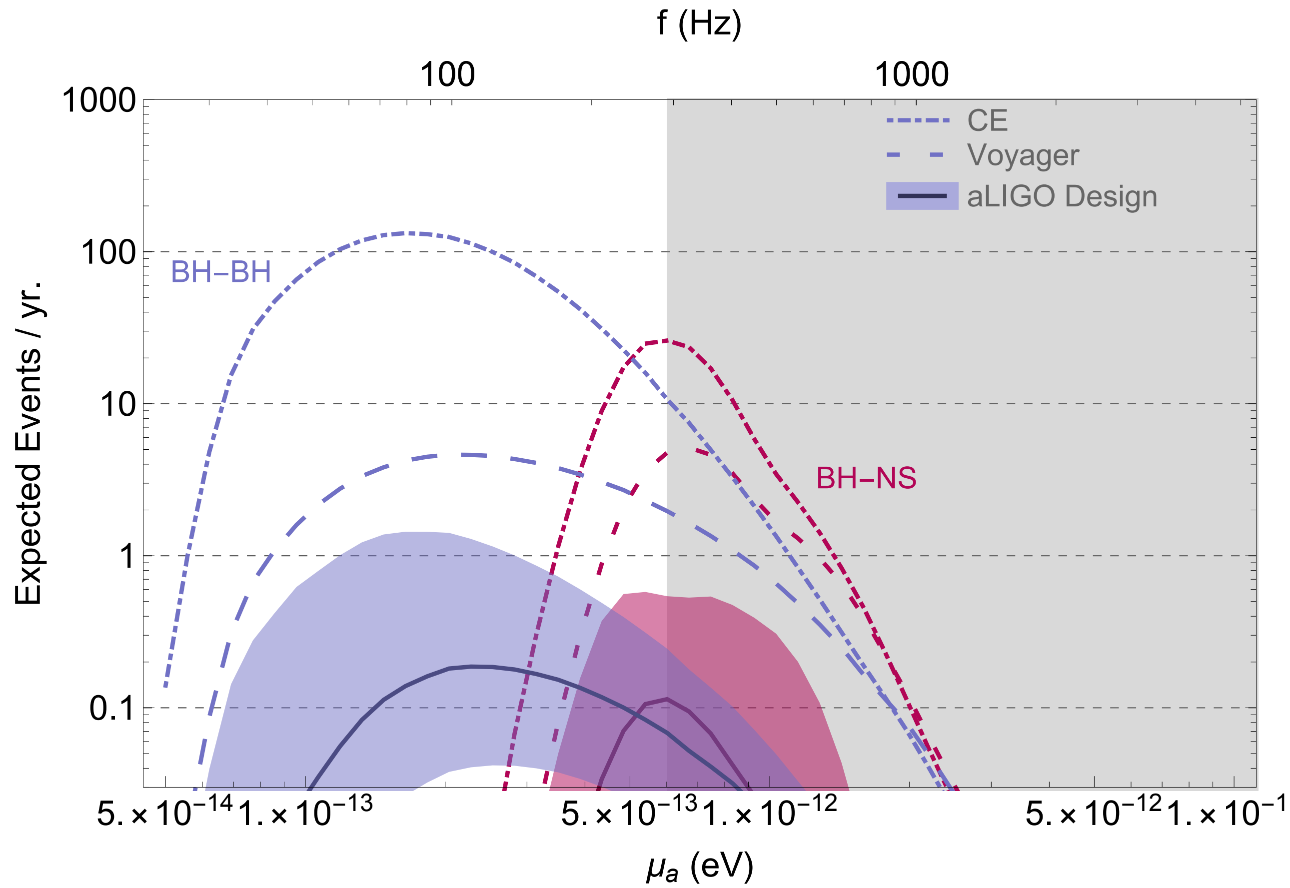

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- **Weak, long signals** last for ~ million years, visible from our galaxy, limited by LIGO noise floor
- Event rates up to 10,000 — can be observed and studied in detail
- Searches ongoing with O1/O2 data

- S. J. Zhu, **MB**, M. A. Papa, D. Tsuna, N. Kawanaka, H.B. Eggenstein *2003.xxxxx*
- C. Palomba, et al (2019)

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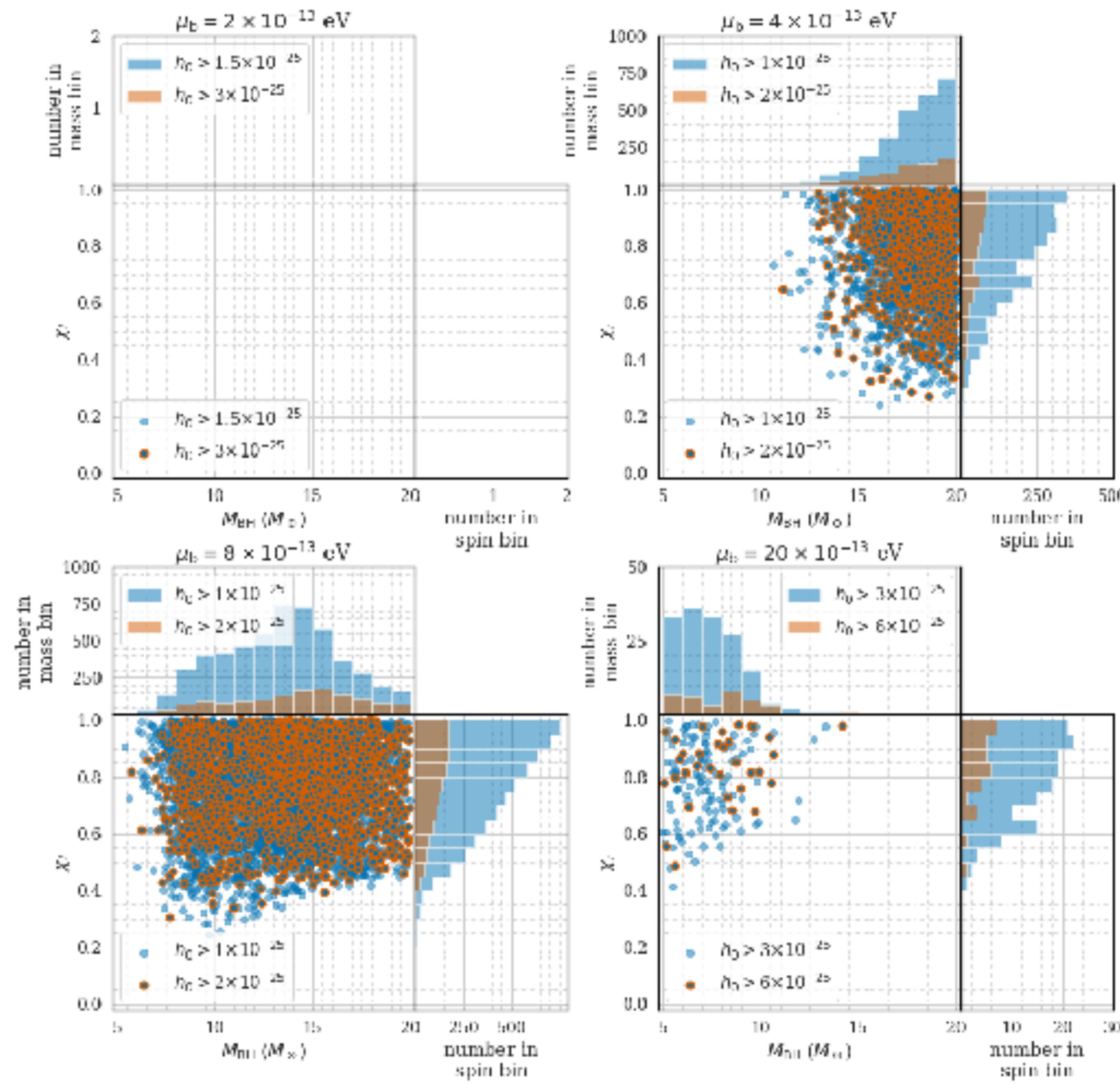

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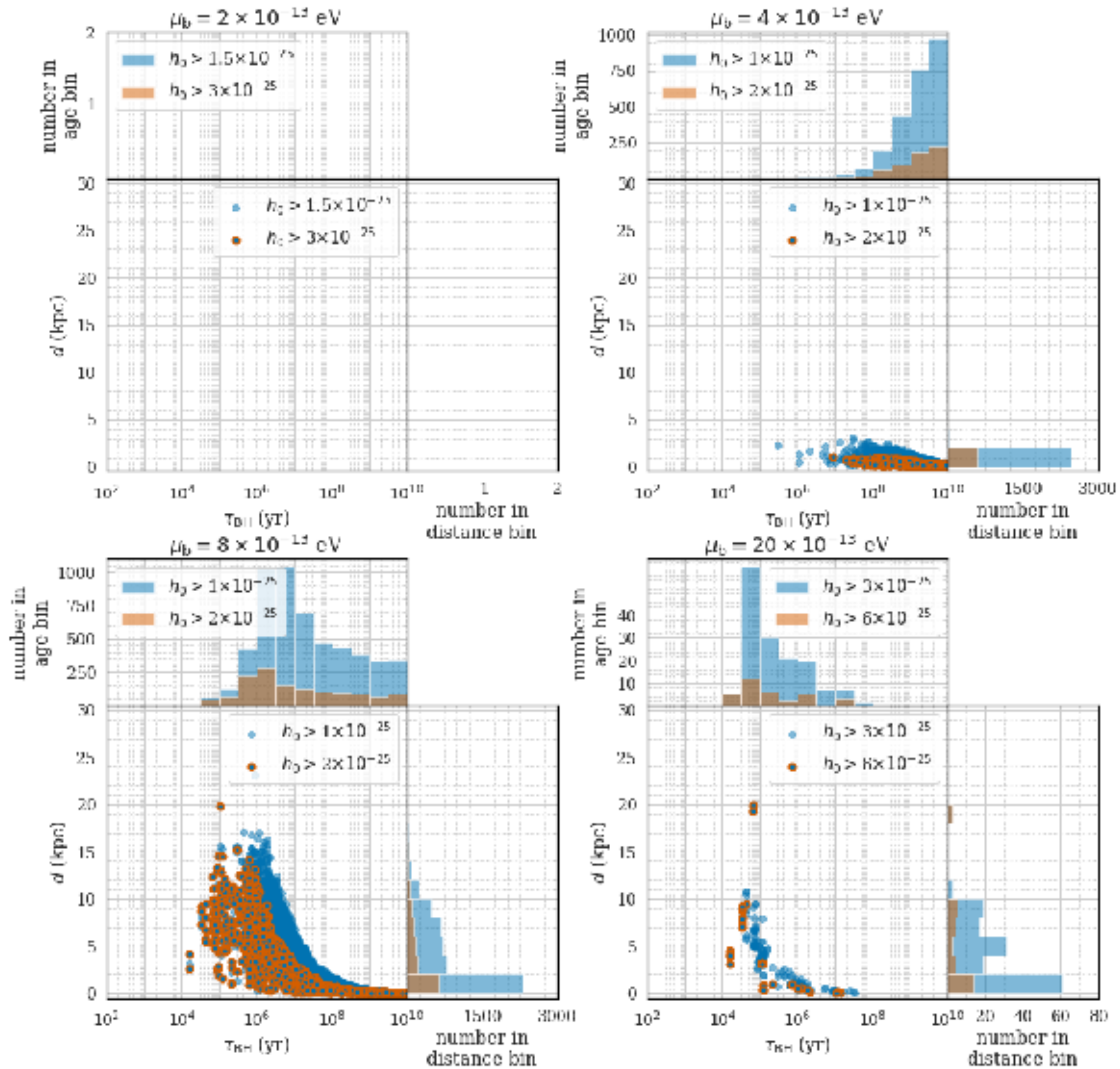
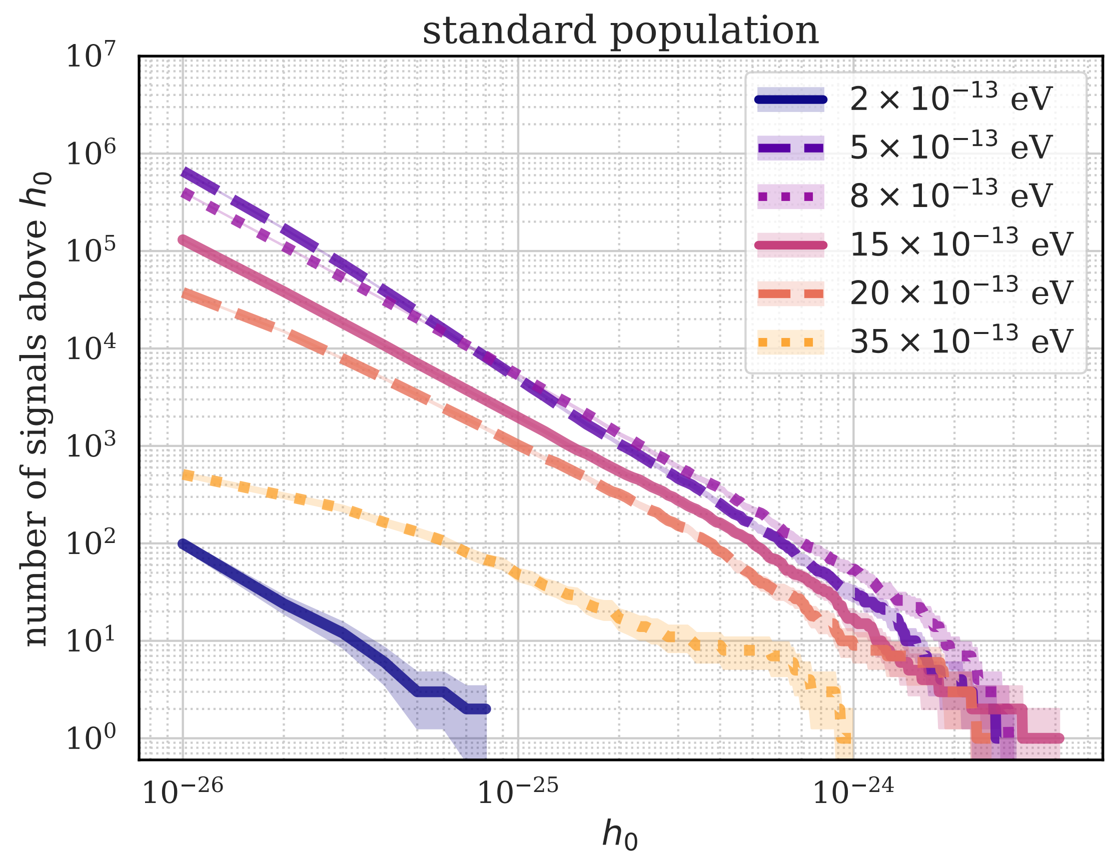
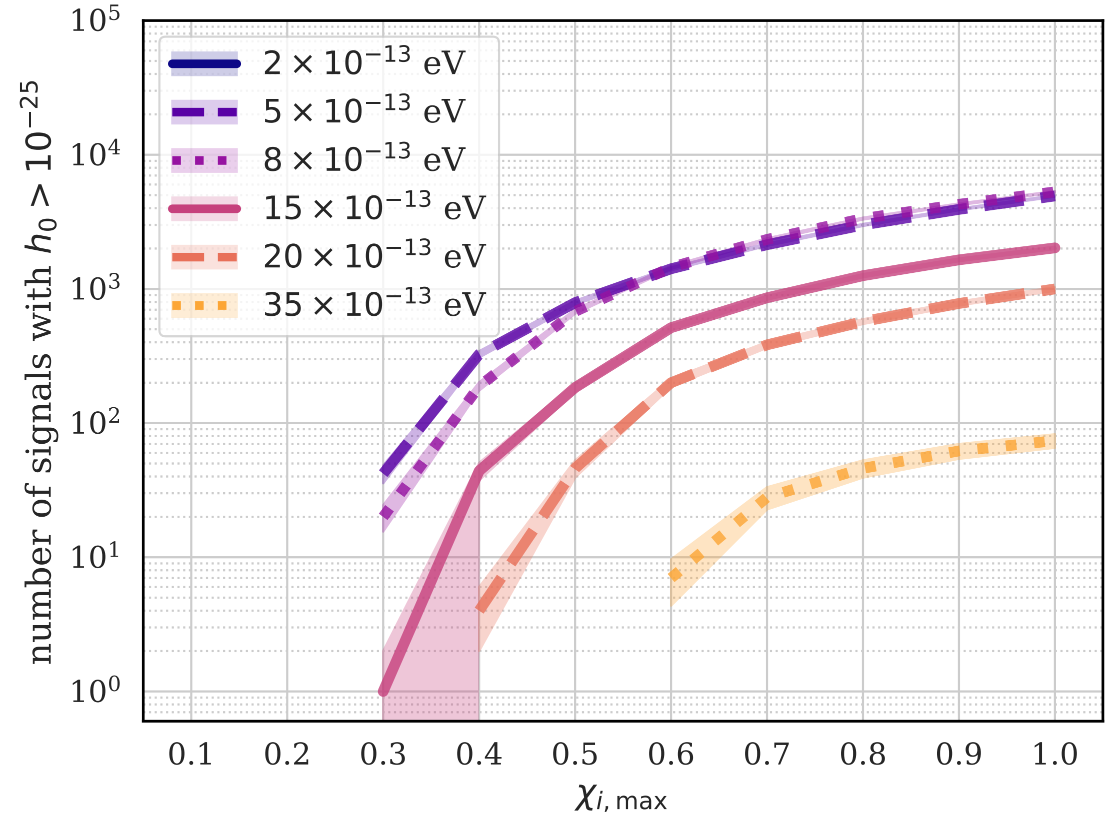


Gravitational Wave Signals

- Expected signal number goes up quickly for lower h0 sensitivities
- Expected signal number decreases with decreasing upper spin





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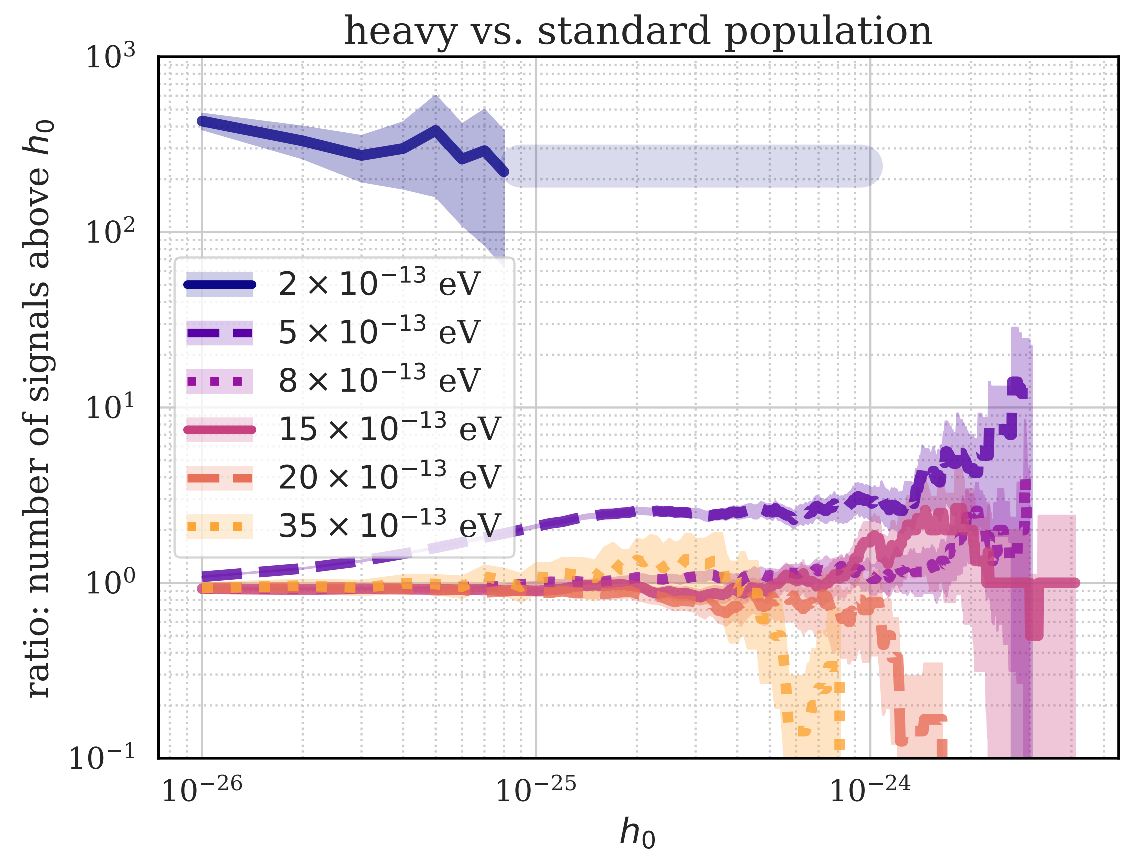
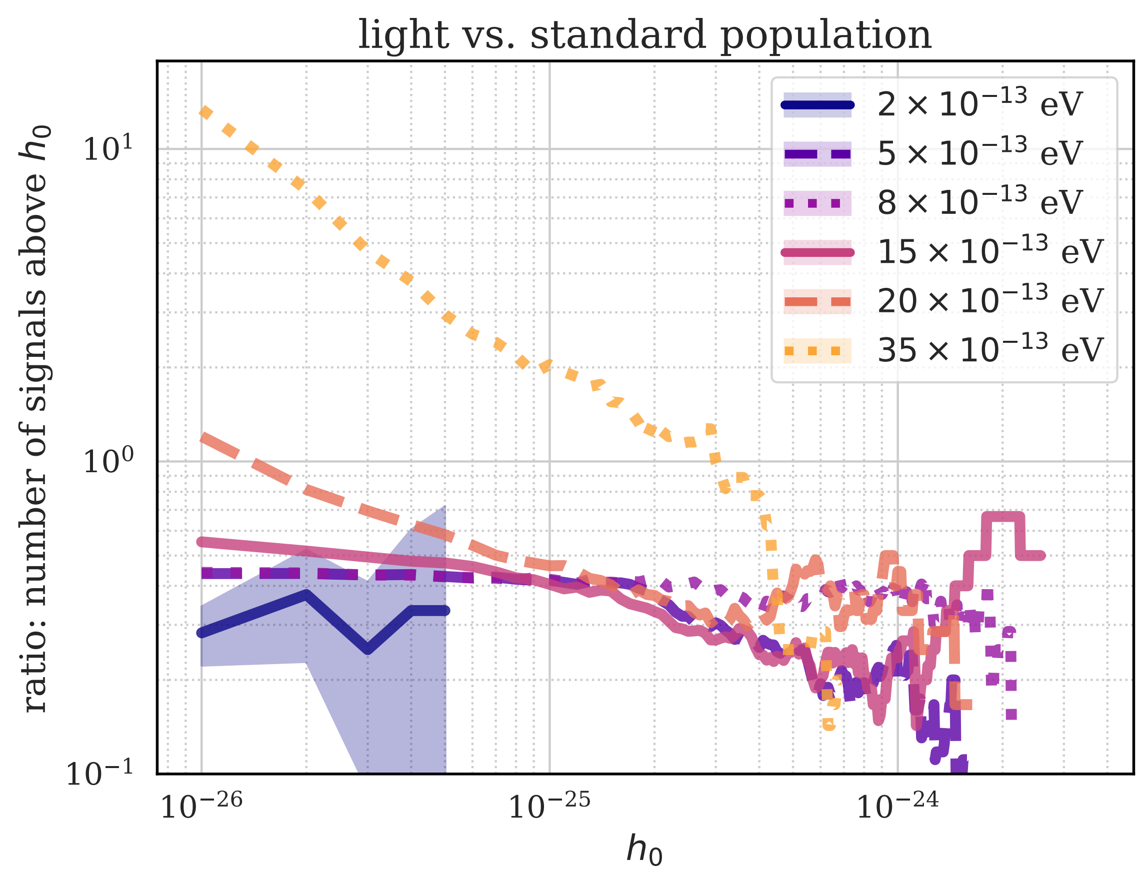
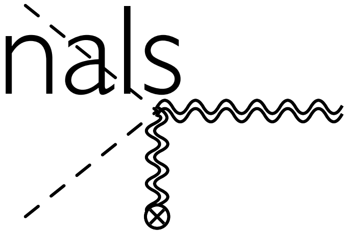
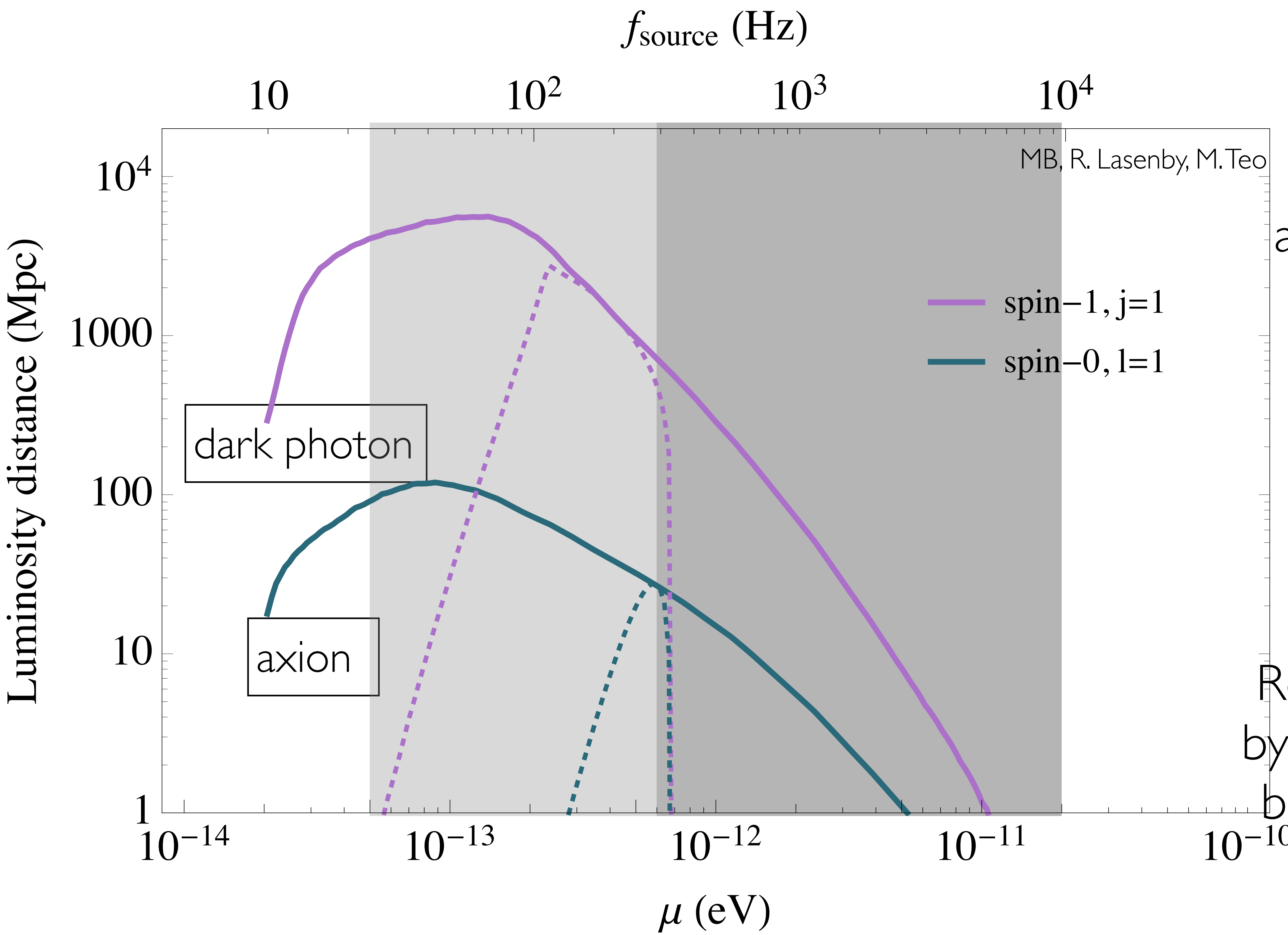




Gravitational Wave Signals





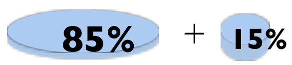
Spin-1 particle annihilations give higher rates, but more constrained

Realistically, limited by number of heav black holes (>100 Msun)

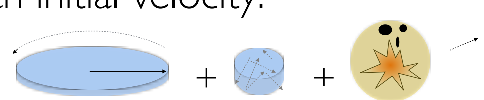
Gravitational Wave Signals:
isolated black holes in the Galaxy

galaxy = disk + bulge + halo

black holes are born:

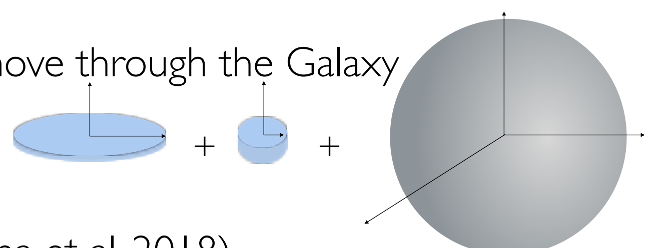


with an initial velocity:



natal kicks

and move through the Galaxy



(see D.Tsuna et al. 2018)

Population of 10⁸ black holes

mass: power-law distribution

$M_{\rm BH} \in [5M_\odot, 20M_\odot]$

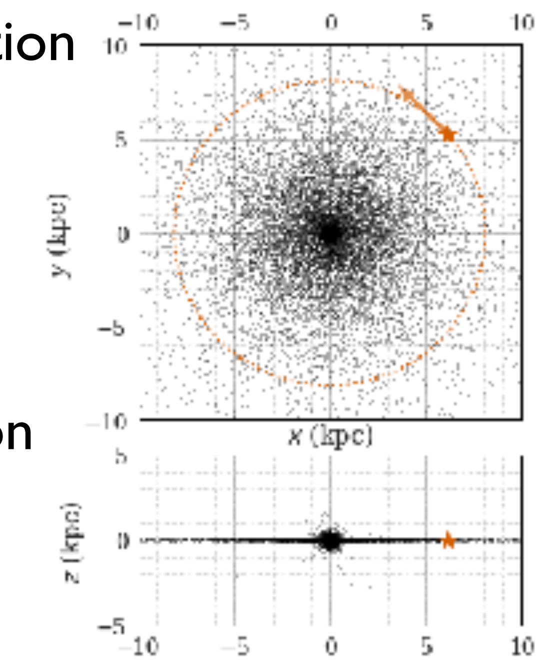
$M_{\rm BH} \in [5M_\odot, 30M_\odot]$

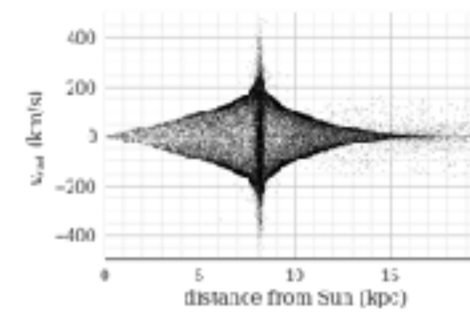
spin: uniform distribution

$\chi_i \in [0, 1]$

$\chi_i \in [0, 0.5]$

$\chi_i \in [0, 0.3]$

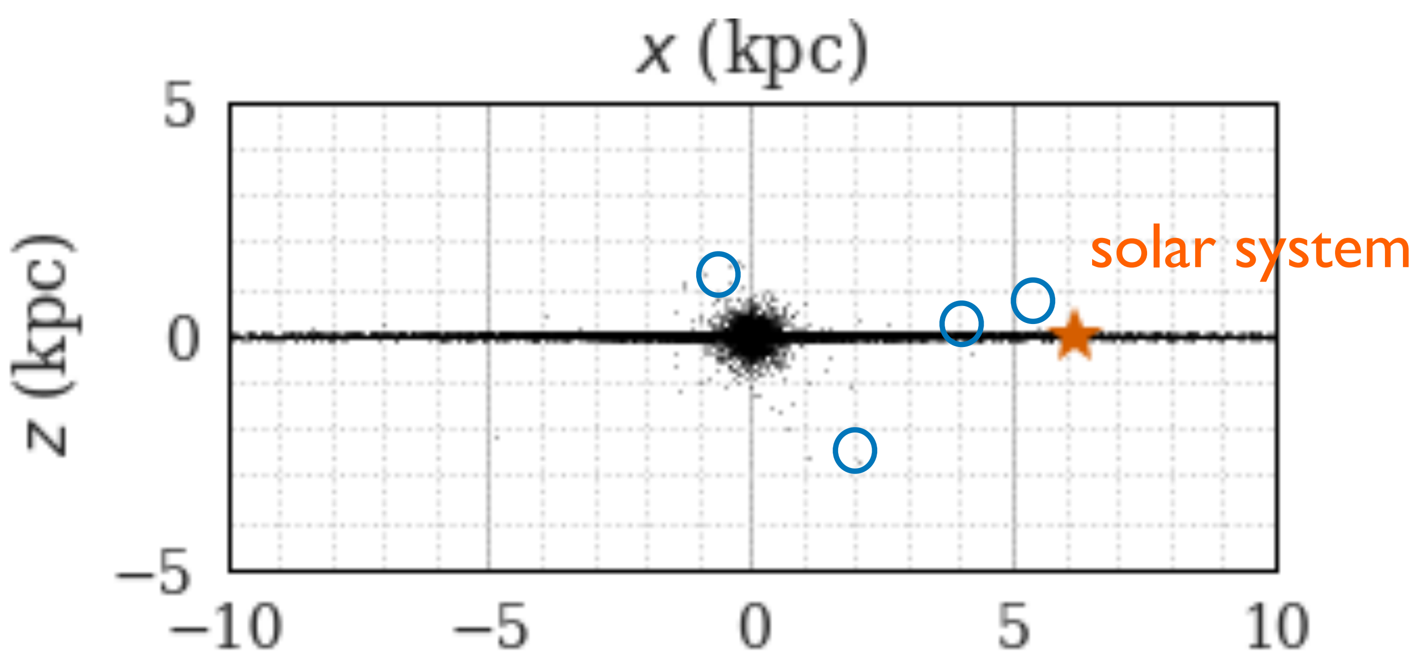




S. J. Zhu, **MB,** M. A. Papa, D.Tsuna, N. Kawanaka, H.B. Eggenstein *(in prep)*

Gravitational Wave Signals

- Simulated population of 10^8 black holes throughout Milky Way
- Each can potentially grow a cloud of axions and subsequently source gravitational waves



black holes born throughout Milky Way, drawn from spin and mass distributions

mass: power-law distribution

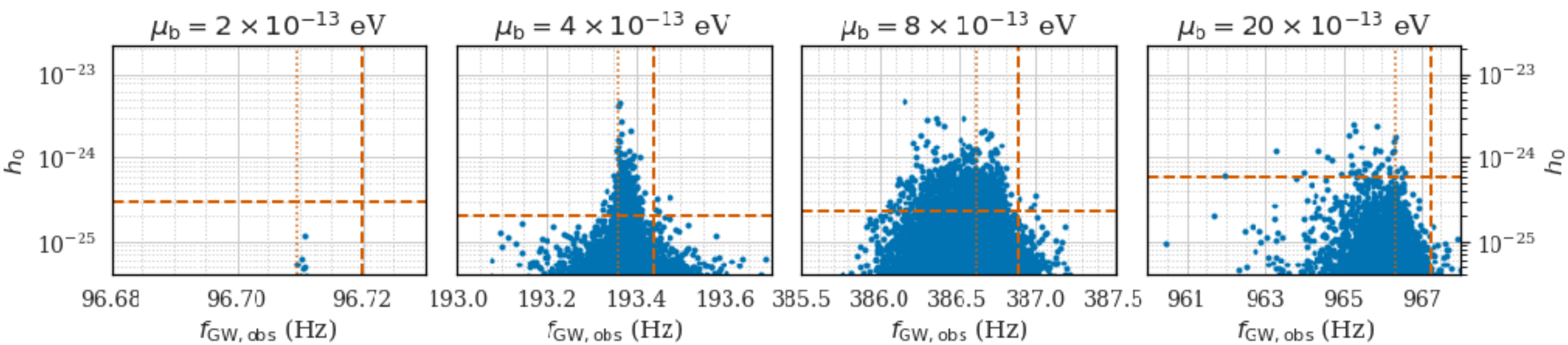
$$M_{\rm BH} \in [5M_\odot, 20M_\odot]$$
$$M_{\rm BH} \in [5M_\odot, 30M_\odot]$$

spin: uniform distribution

$$\chi_i \in [0, 1]$$
$$\chi_i \in [0, 0.5]$$
$$\chi_i \in [0, 0.3]$$

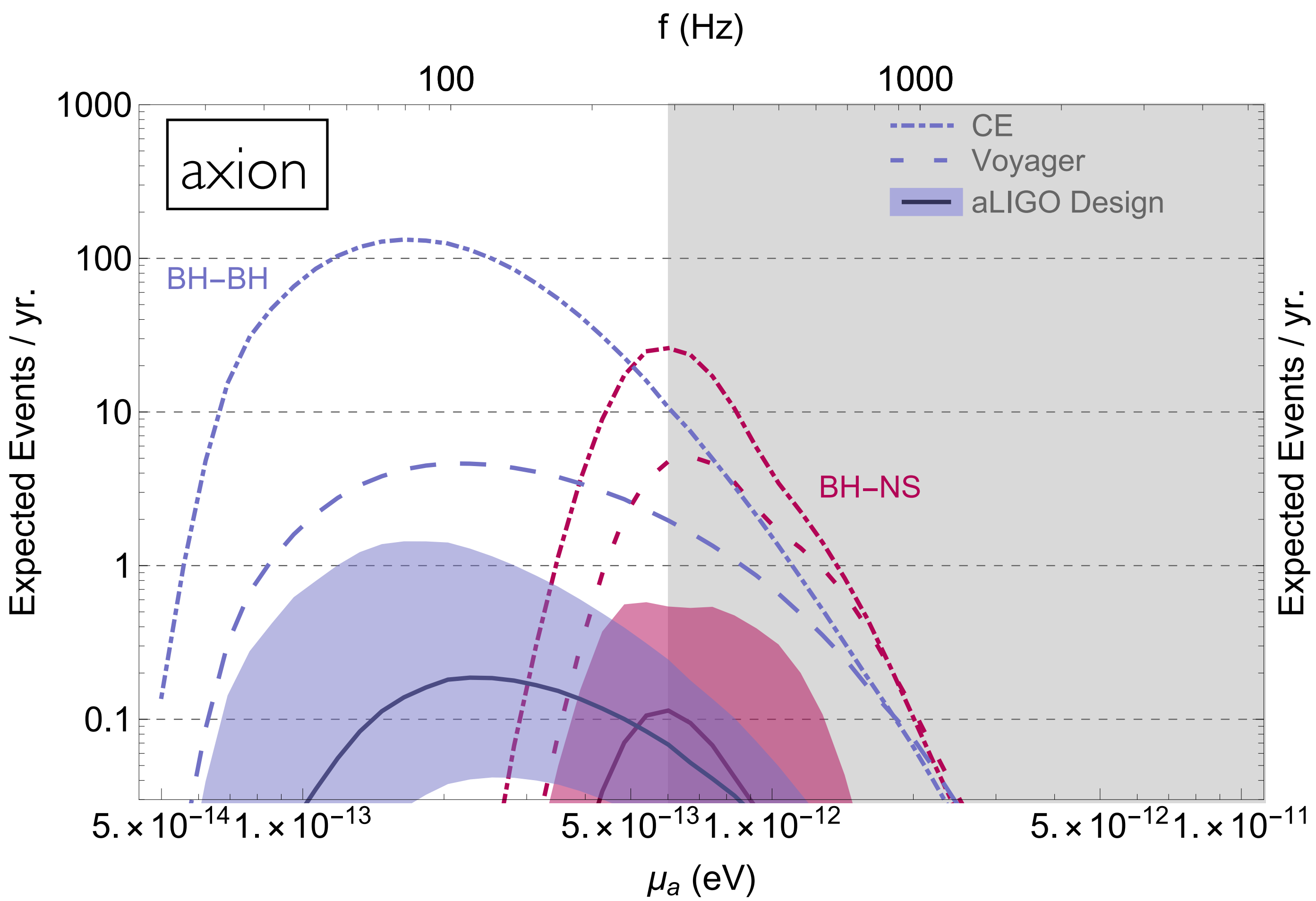
Zhu, **MB**, Papa, Tsuna, Kawanaka, Eggenstein (2003.03359)

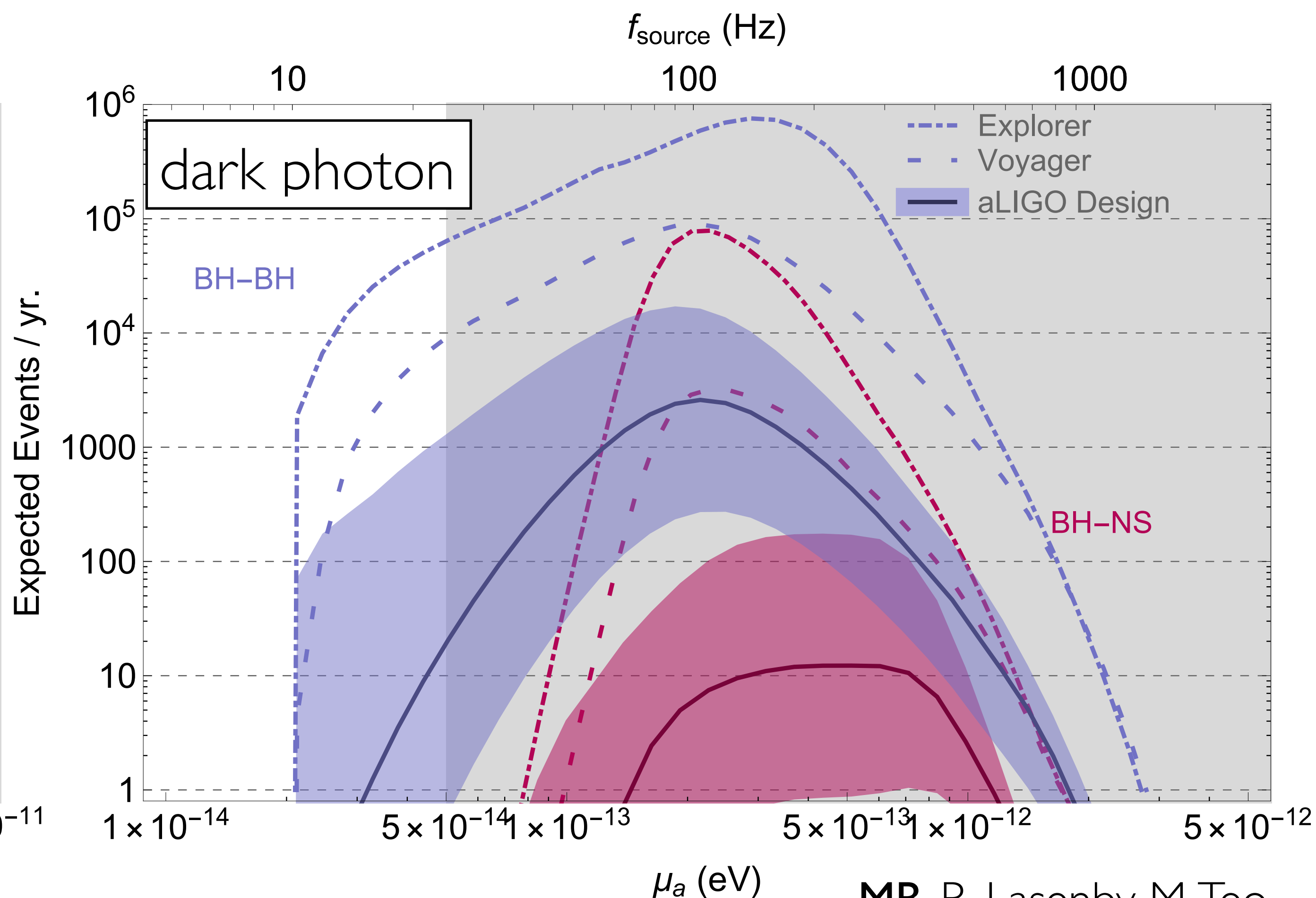
Gravitational Wave Signals



- Signals appear in the detector clustered around single frequency at twice the axion mass
- If one signal is detectable, expect many with a unique density profile

Gravitational Wave Signals





MB, R. Lasenby, M. Teo

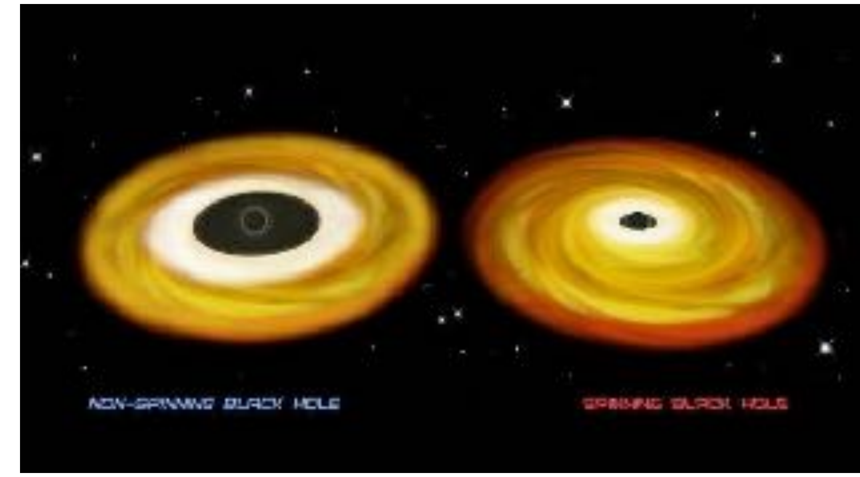
A. Arvanitaki, **MB**, S. Dimopoulos, S. Dubovsky, R. Lasenby

- **Short, bright signals** — directed follow-up searches to recently born BHs from 10-1000 Mpc away
- Measure BH mass, spin, and particle mass: fully study gravitational atom
- Especially promising at future GW observatories, methods investigations ongoing
    - M. Isi, L. Sun, R. Brito, A. Melatos

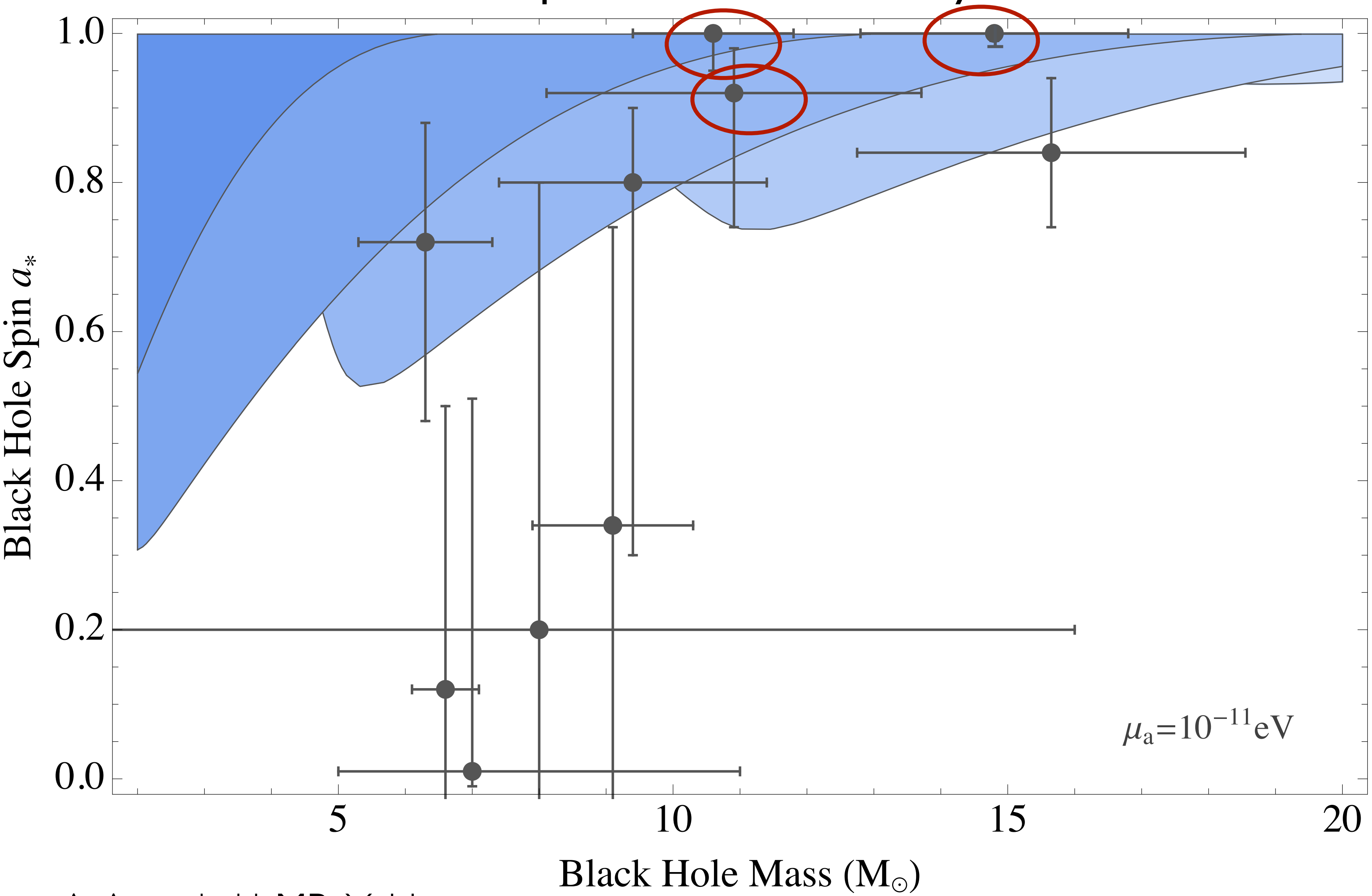
Black hole spins

Black Hole Spins

Black hole spin and mass measurements can be used to constrain axion parameter space



Black hole spins measured in X-ray binaries

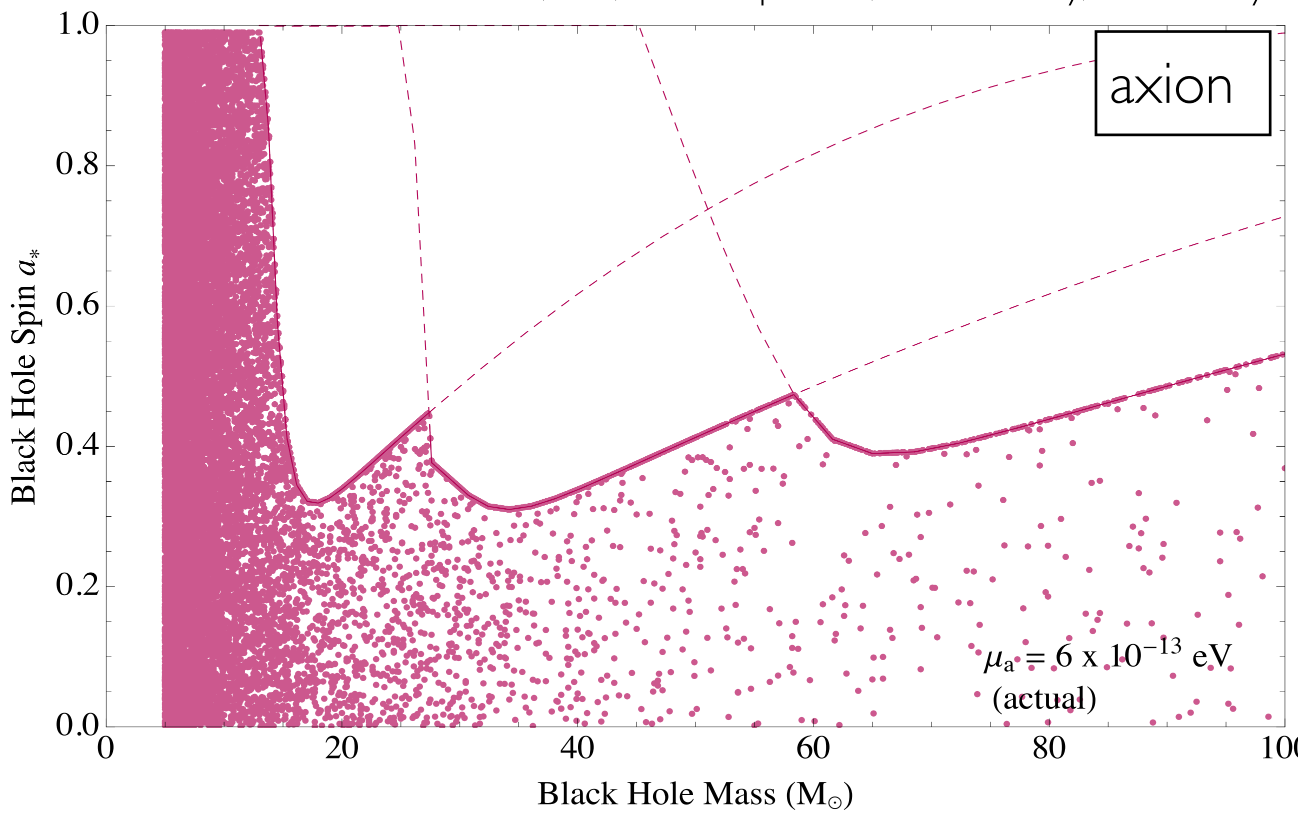


A. Arvanitaki, **MB**, X. Huang

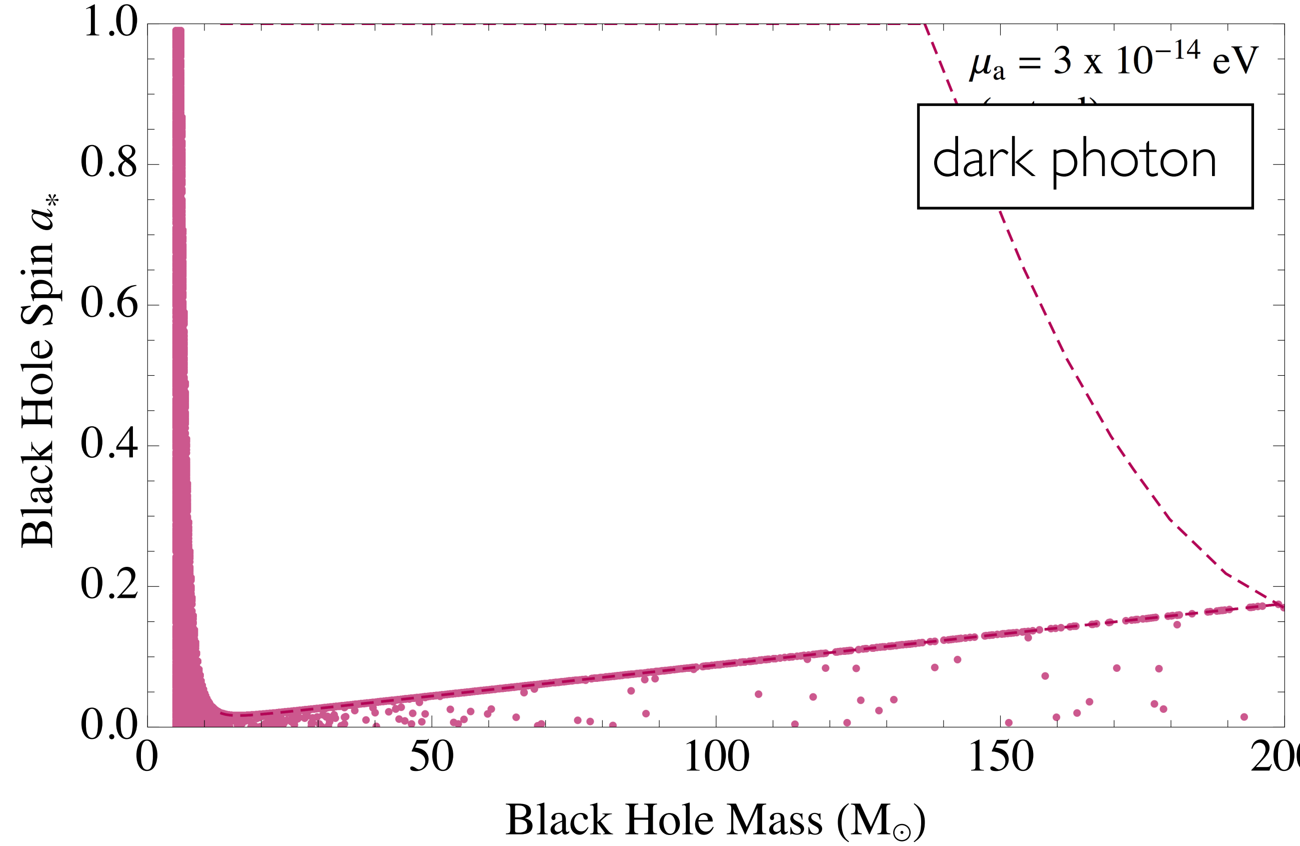
Black Hole Spins
at LIGO

If light axion exists, some initial merger BHs would have low spin due to superradiance, limited by age of binary system

A. Arvanitaki, **MB**, S. Dimopoulos, S. Dubovsky, R. Lasenby



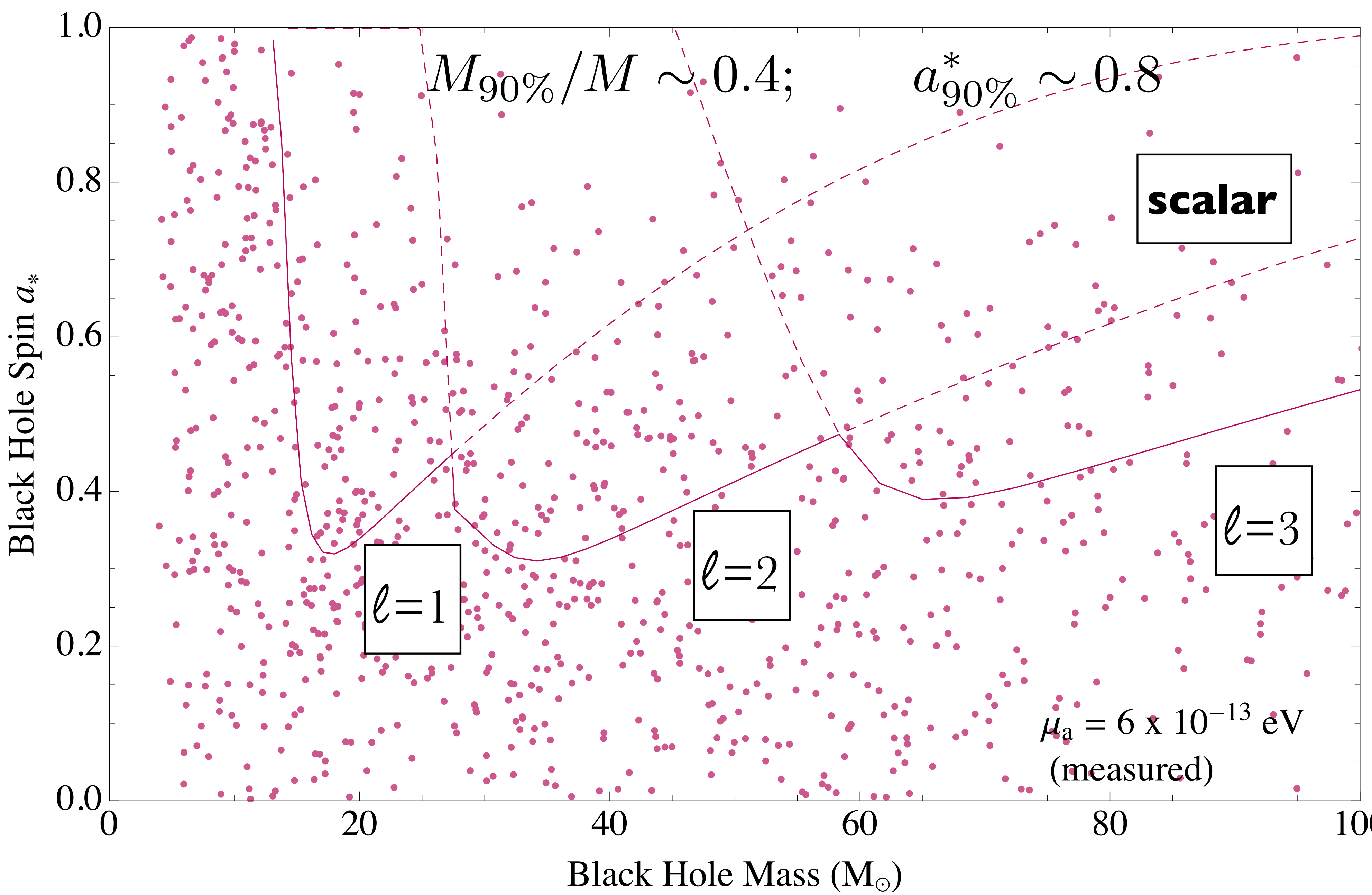
MB, R. Lasenby, M. Teo



9-240 BBHs/Gpc^3/yr. — 1000s of BHs merging in low-redshift universe

With ~100-300 spin measurements, possible to see statistical evidence for light boson in the mass range 10^{-11} — 10^{-13} eV

Black Hole Spins

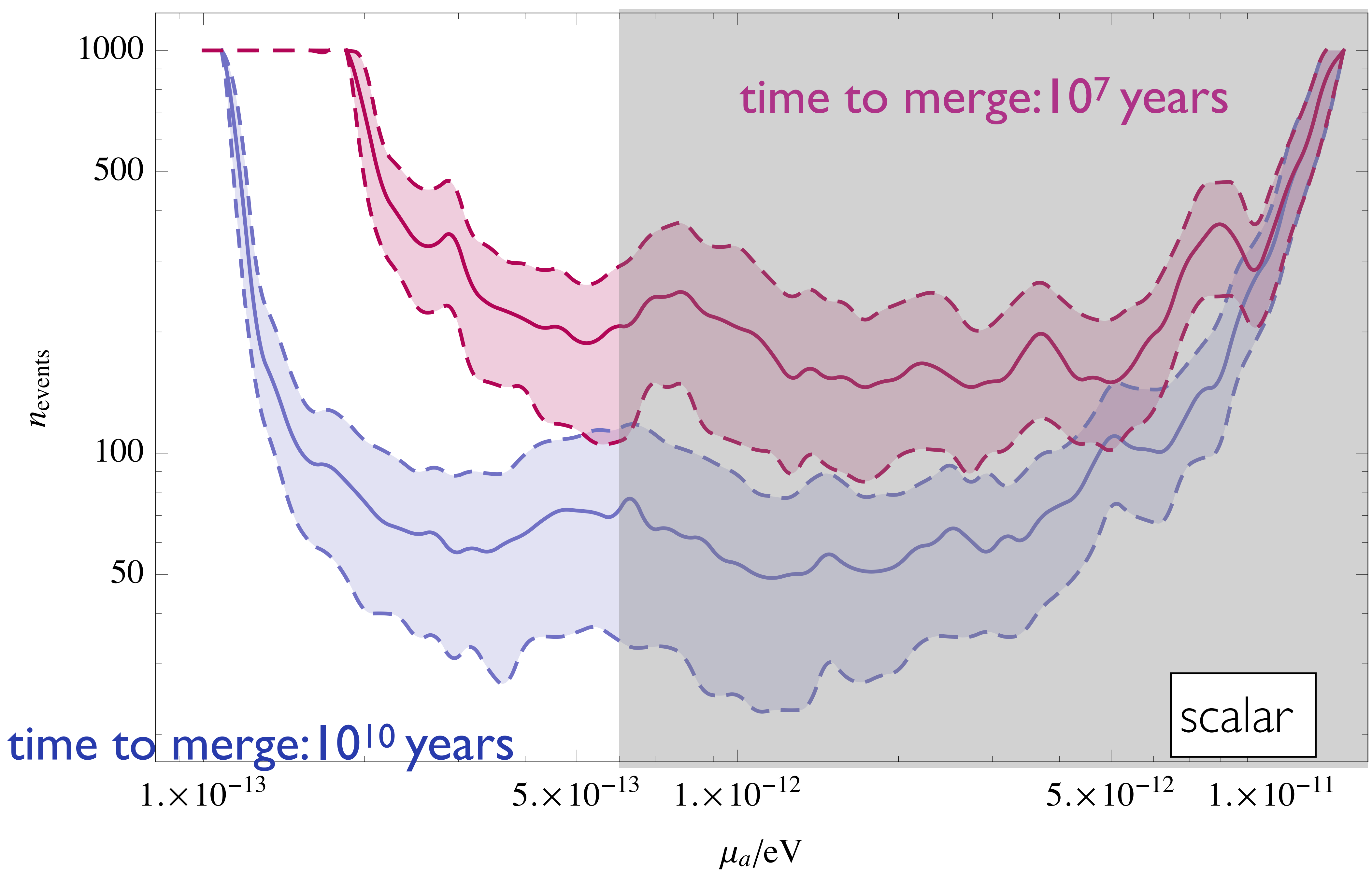


so far:
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814

With ~100 — 300 spin measurements, can find evidence for light boson in the mass range 10^{-11} — 10^{-13} eV

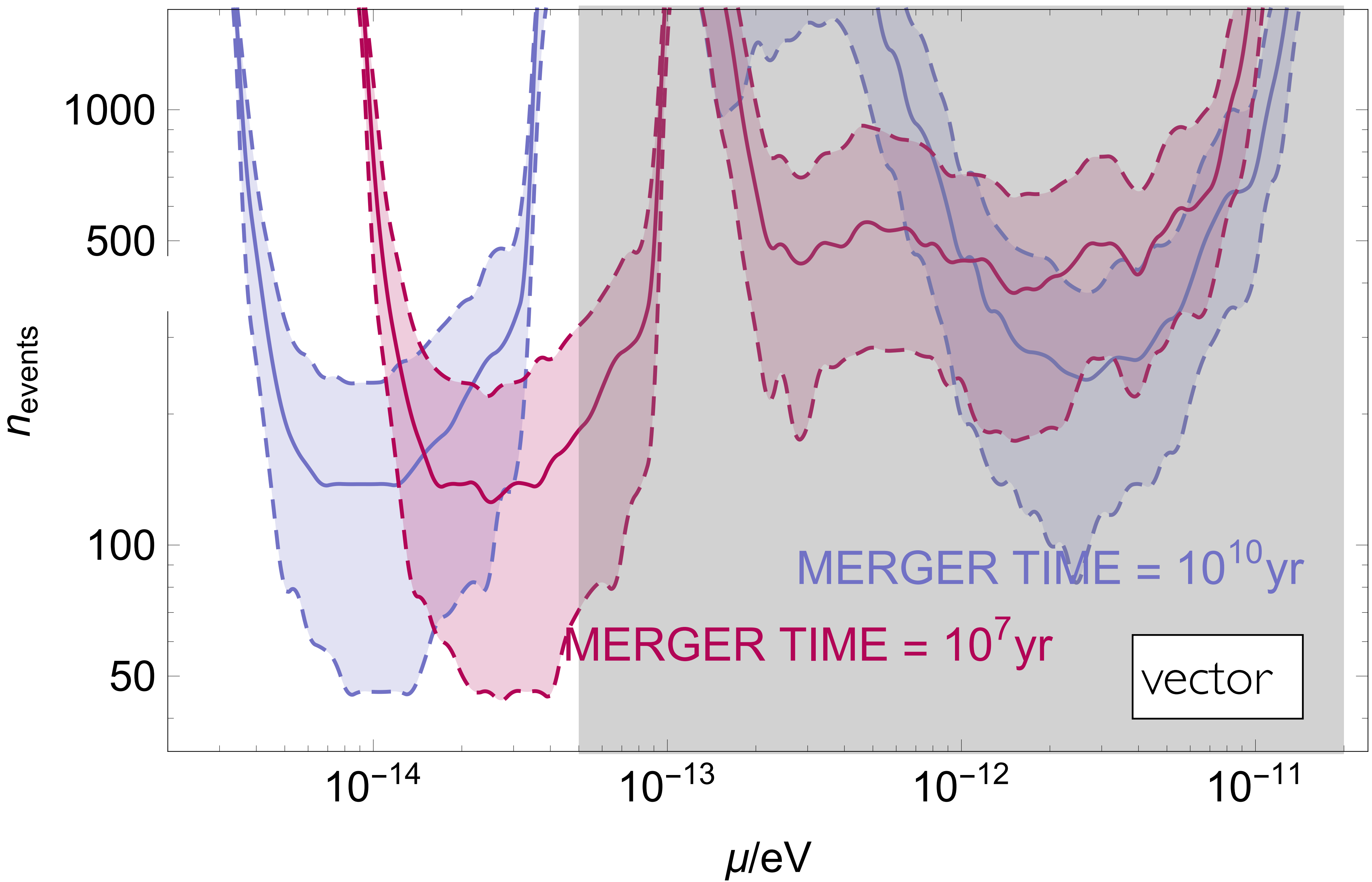
Black Hole Spins

Can find statistical evidence for deficit of high spins in a range of BH masses with 50-200 measurements:



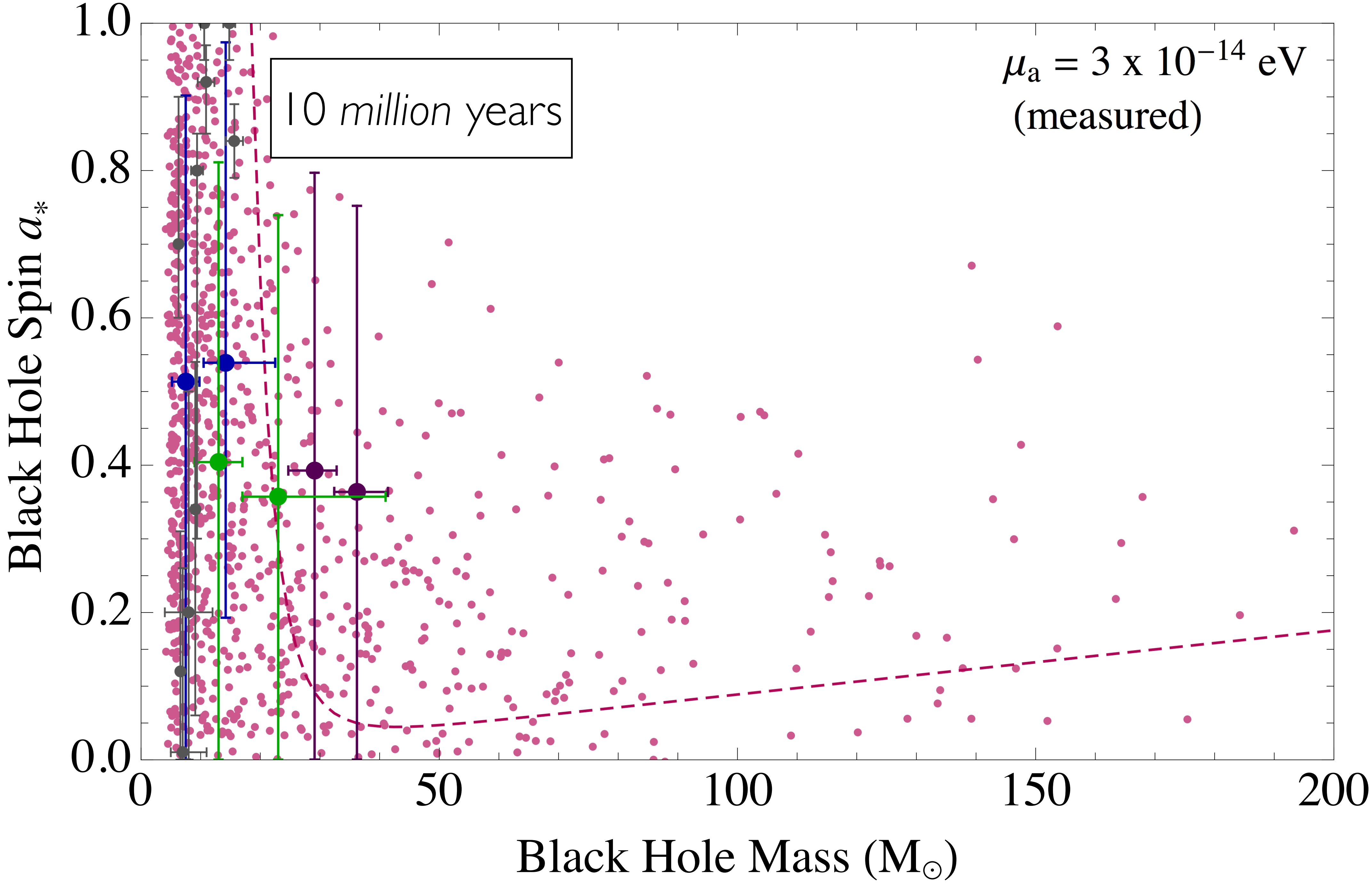
Black Hole Spins

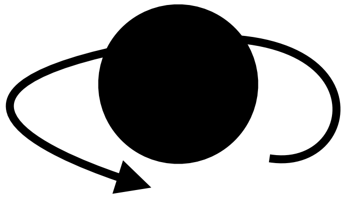
Can find statistical evidence for deficit of high spins in a range of BH masses with 50-200 measurements:



Black Hole Spins

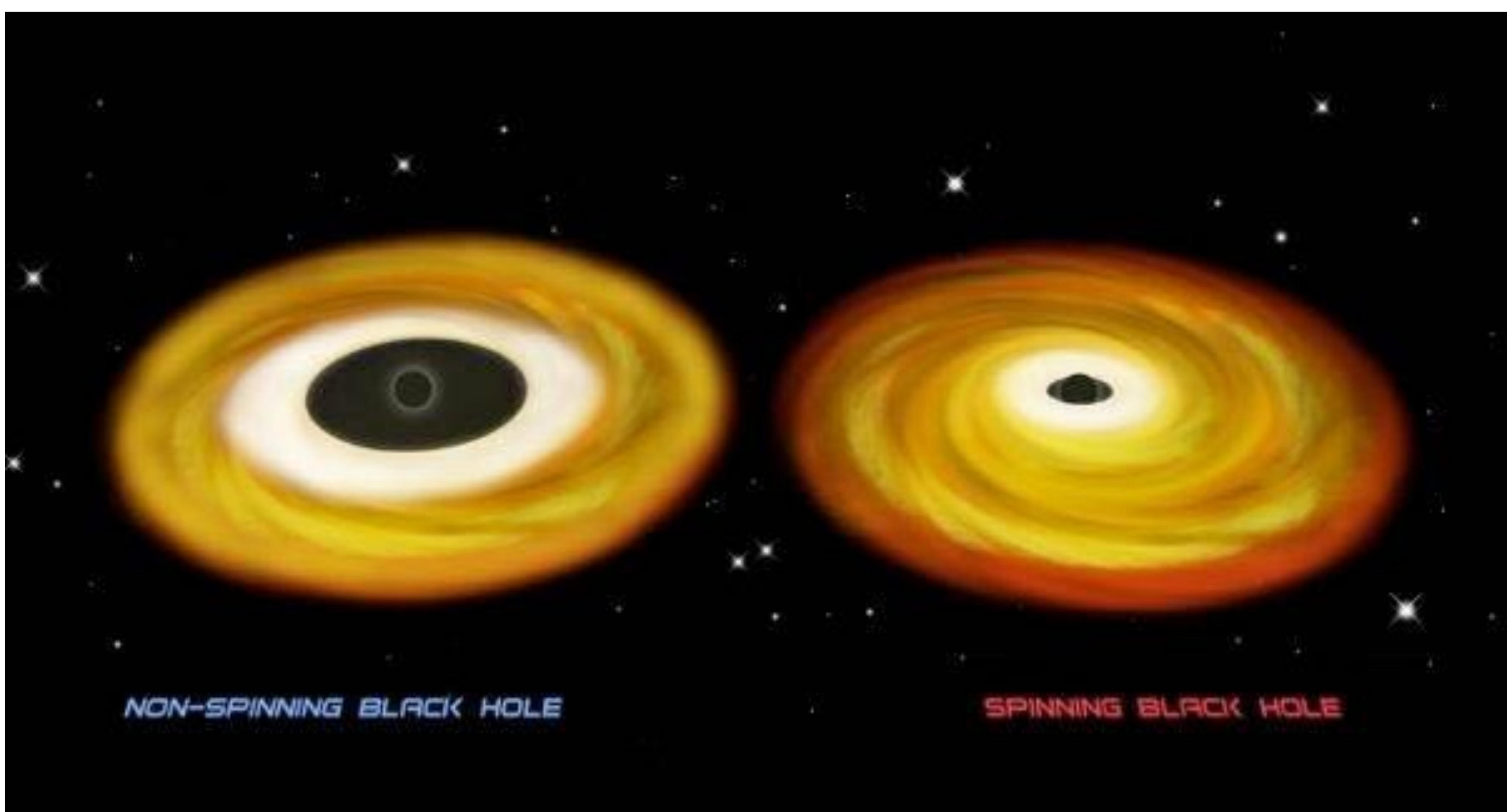
May see spin-down of black holes at LIGO outside of excluded region



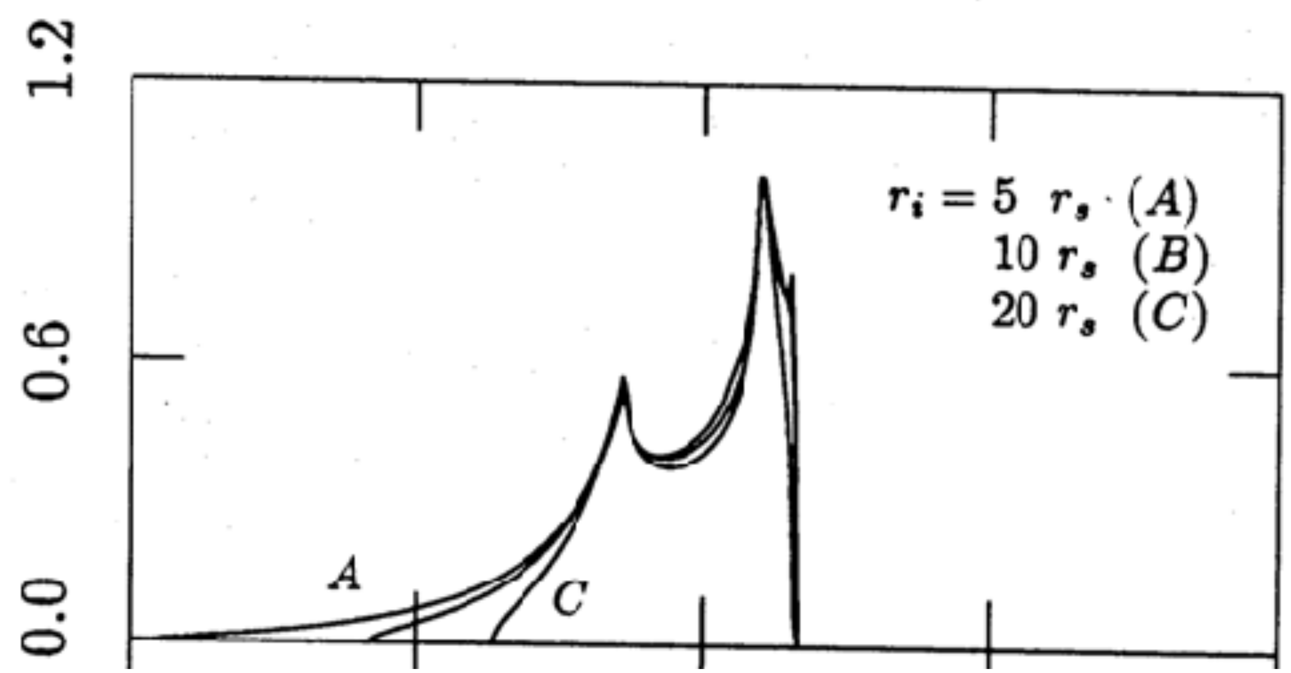


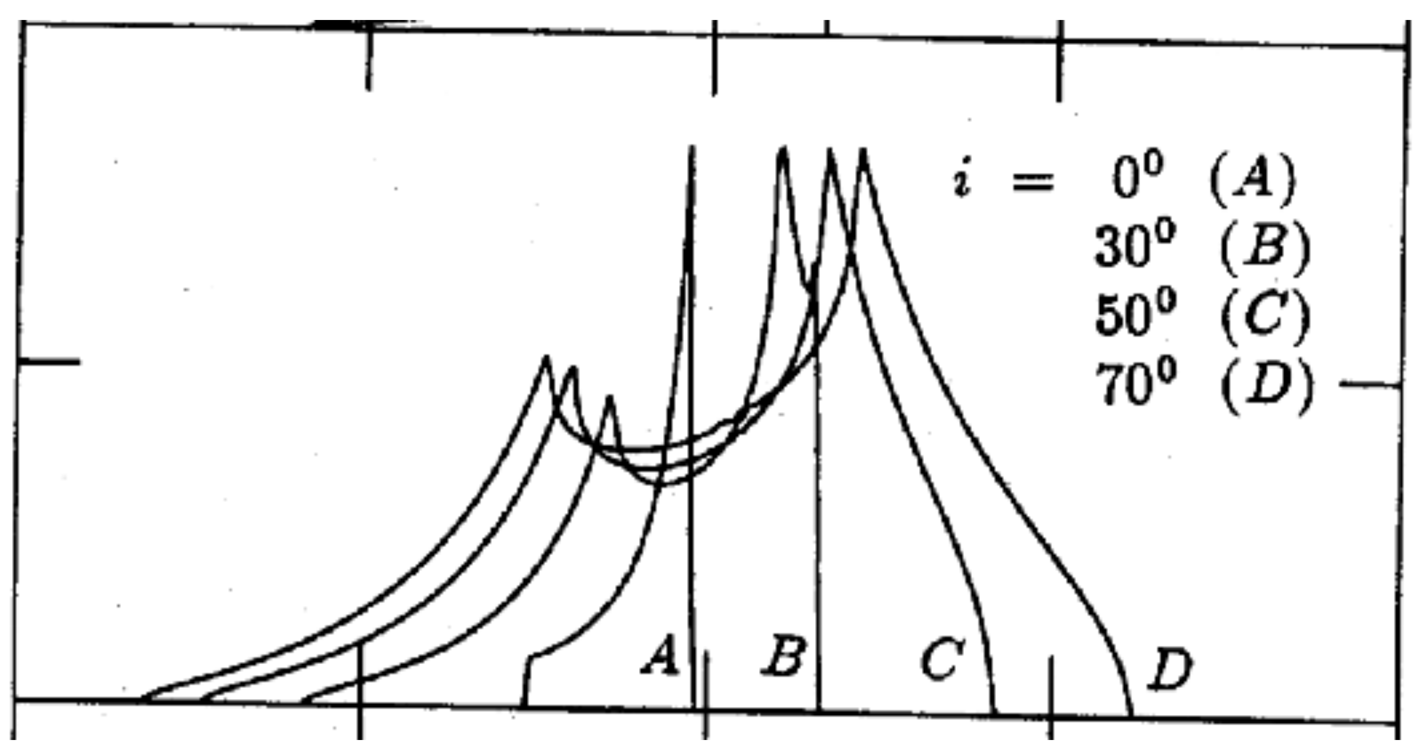
Black Hole Spins

- Two leading methods: continuum fitting and X-ray reflection
- Based on finding the innermost stable orbit of the accretion disk
- Uncertainty dominated by observational errors; smaller at extremal spins



Xray line BH spin measurement





Continuum measurement

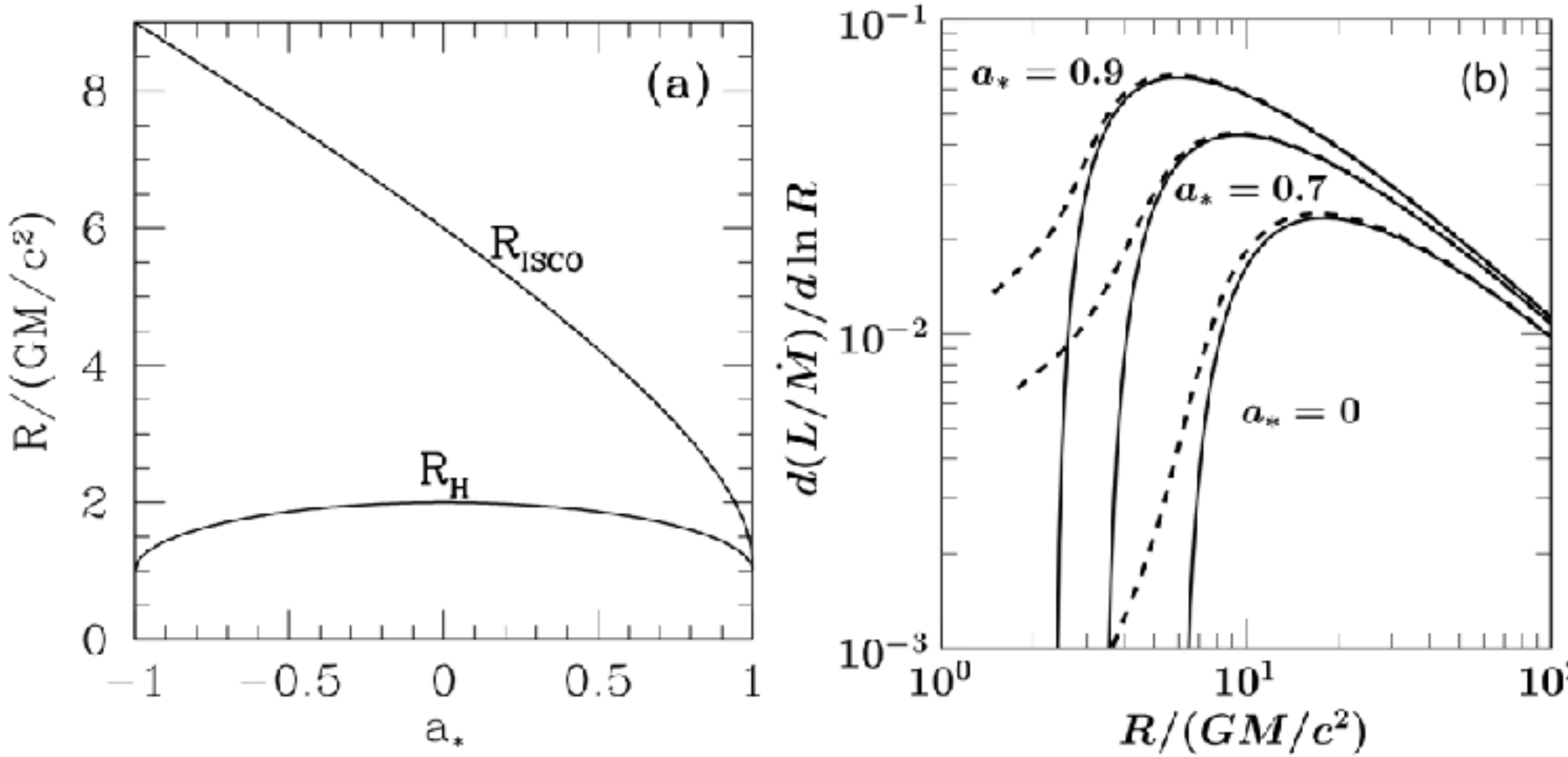


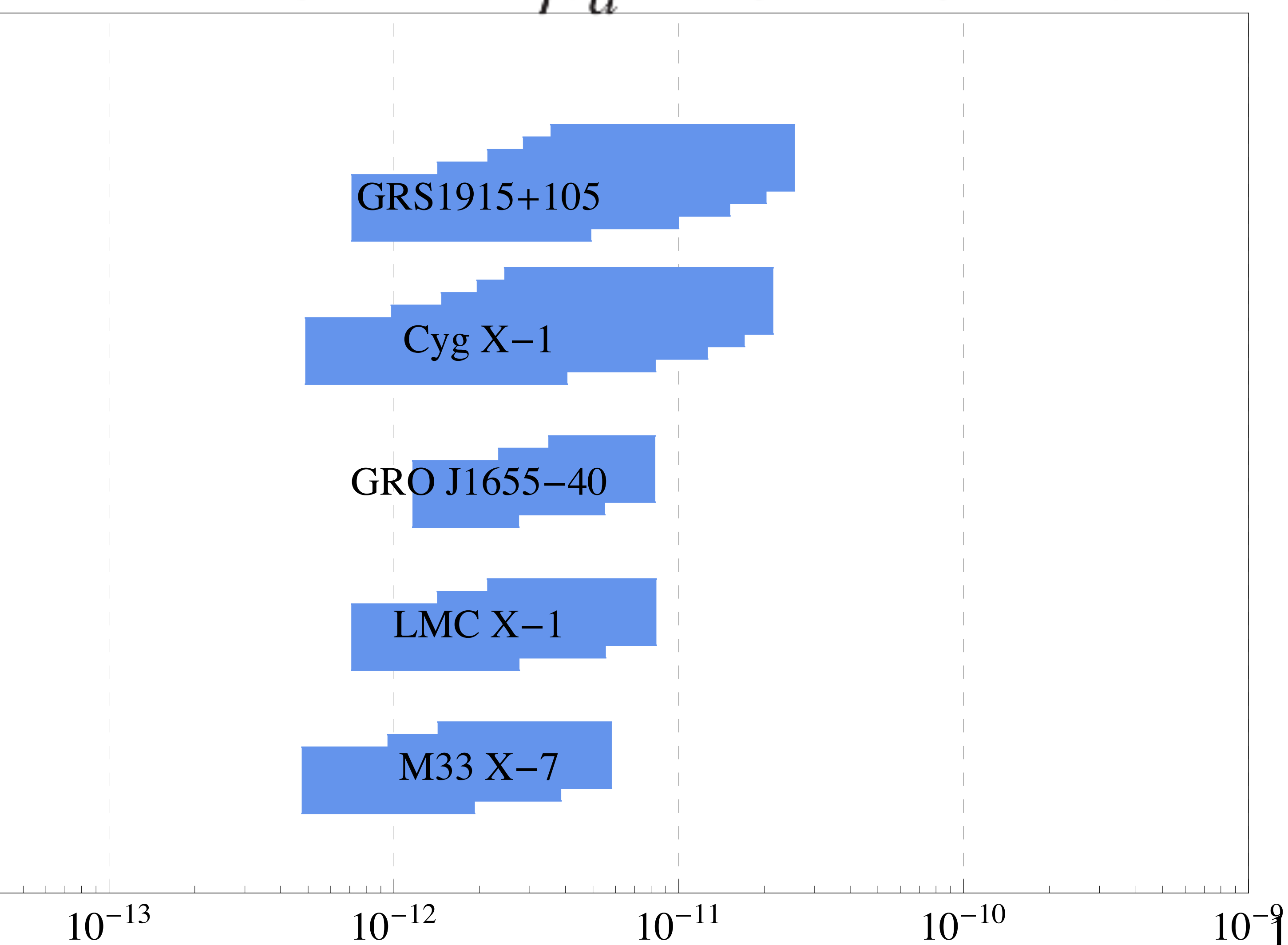
Fig. 3 (a) Radius of the ISCO $R_{\rm ISCO}$ and of the horizon $R_{\rm H}$ in units of GM/c^2 plotted as a function of the black hole spin parameter a_*. Negative values of a_* correspond to retrograde orbits. Note that $R_{\rm ISCO}$ decreases monotonically from $9GM/c^2$ for a retrograde orbit around a maximally spinning black hole, to $6GM/c^2$ for a non-spinning black hole, to GM/c^2 for a prograde orbit around a maximally spinning black hole. (b) Profiles of $d(L/\dot{M})/d\ln R$, the differential disk luminosity per logarithmic radius interval normalized by the mass accretion rate, versus radius $R/(GM/c^2)$ for three values of a_*. Solid lines are the predictions of the NT model. The dashed curves from Zhu et al. (2012), which show minor departures from the NT model, are discussed in Section 5.2.

Black Hole Spins

Five stellar black holes and four SMBHs combine to disfavor the range:

scalar

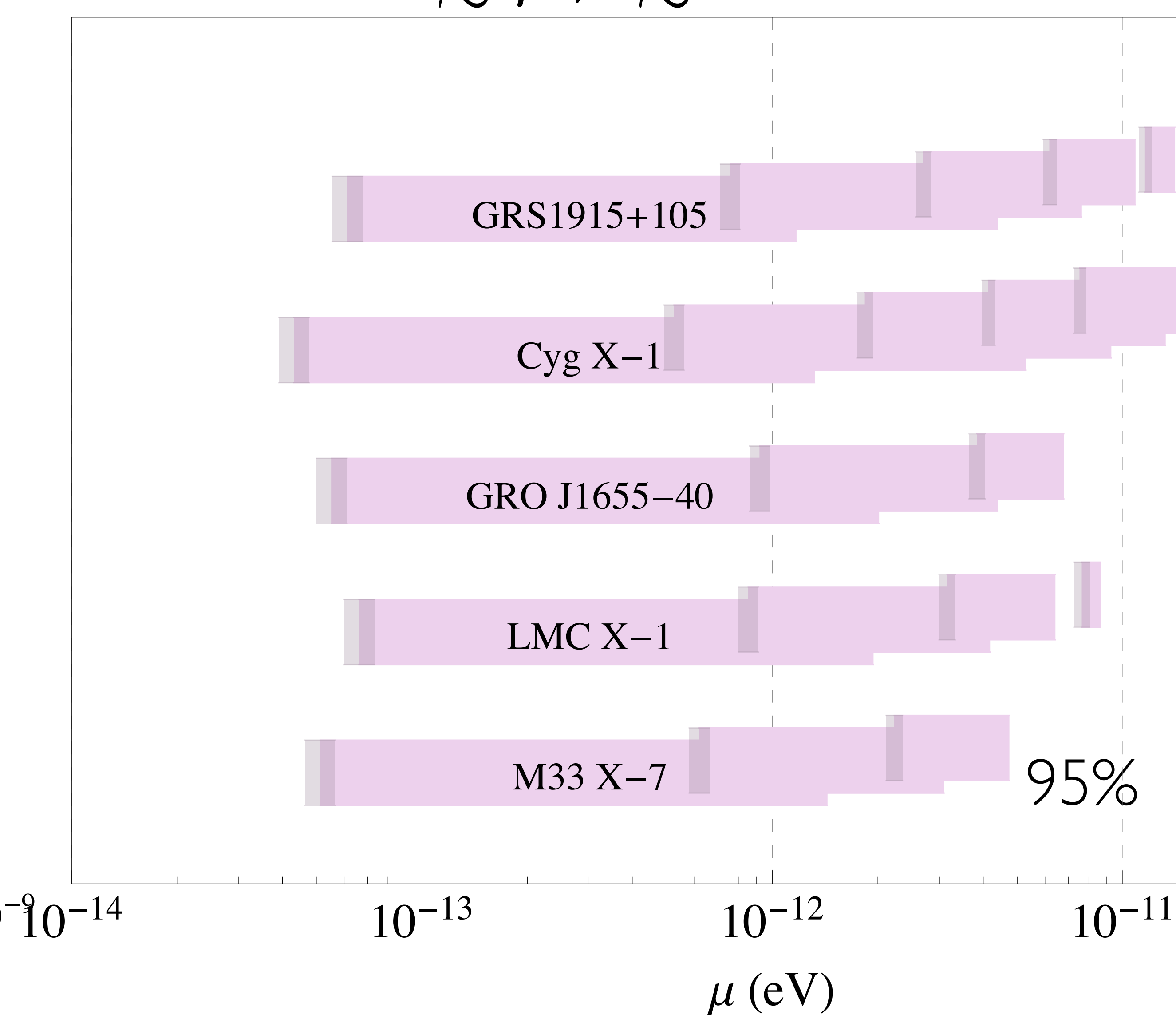
$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13}\ \text{eV}$$



$$3 \times 10^{17} < f_a < 1 \times 10^{19}\ \text{GeV}$$

vector

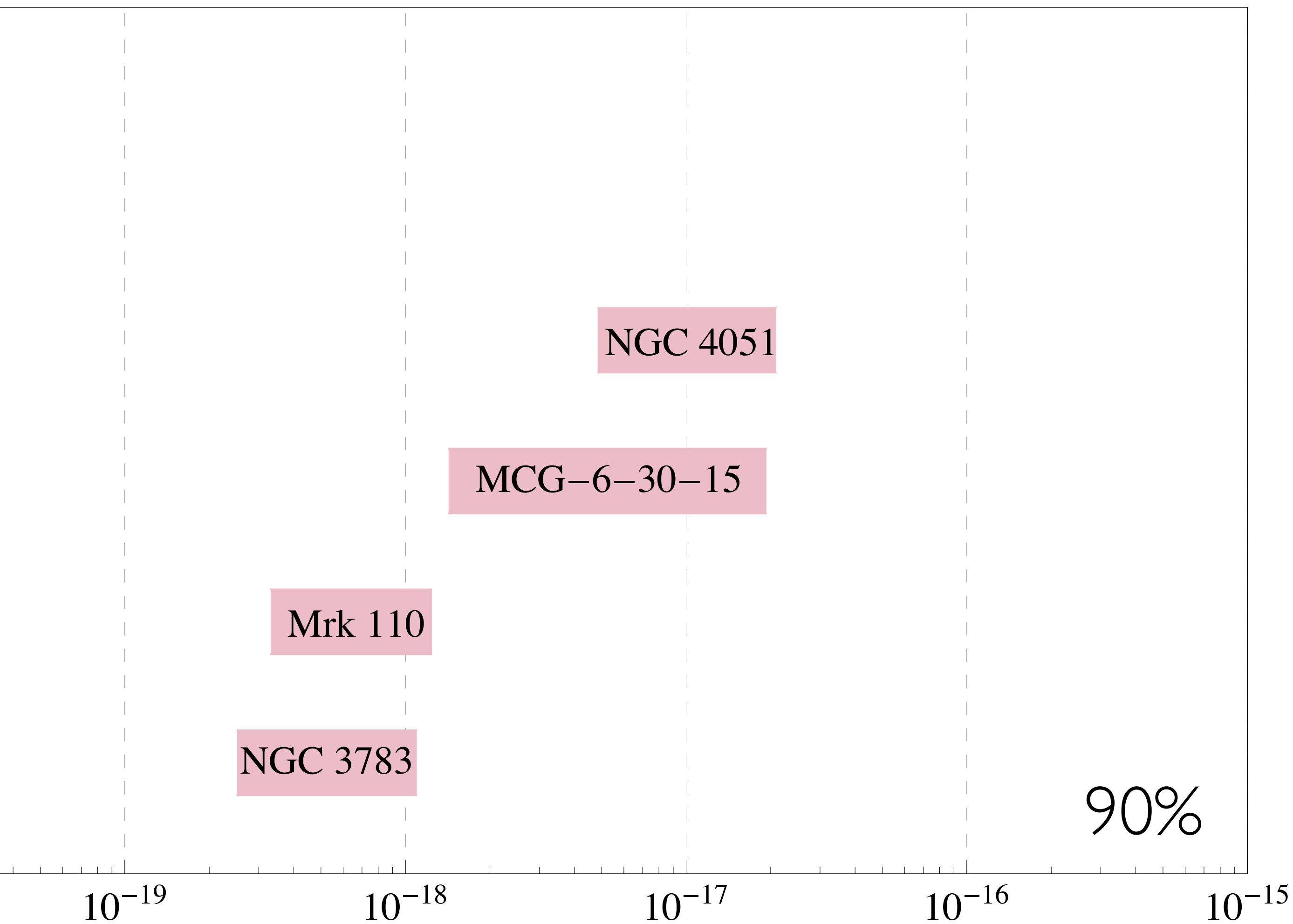
$$2 \times 10^{-11} \gtrsim \mu_V \gtrsim 5 \times 10^{-14}\text{eV}$$



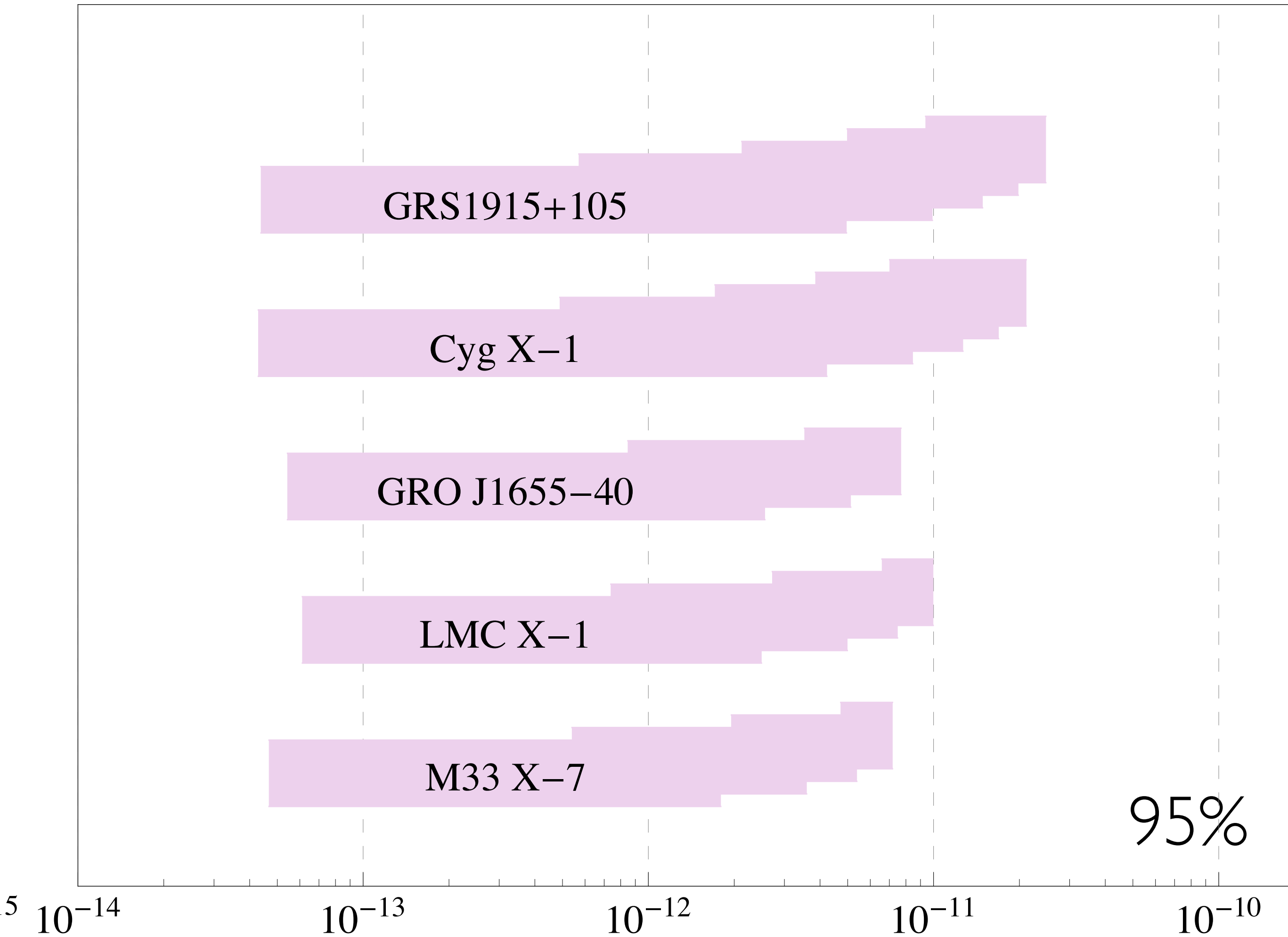
Black Hole Spins

Five stellar black holes and four SMBHs combine to disfavor the range:

$$2.5 \times 10^{-19} < \mu_V < 2.1 \times 10^{-17}\text{eV}$$



$$2 \times 10^{-11} \gtrsim \mu_V \gtrsim 5 \times 10^{-14}\text{eV}$$



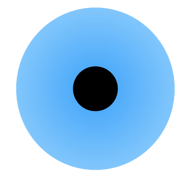
Self Interactions

Self-Interactions

- Relevant processes compete with each other at large field amplitude:

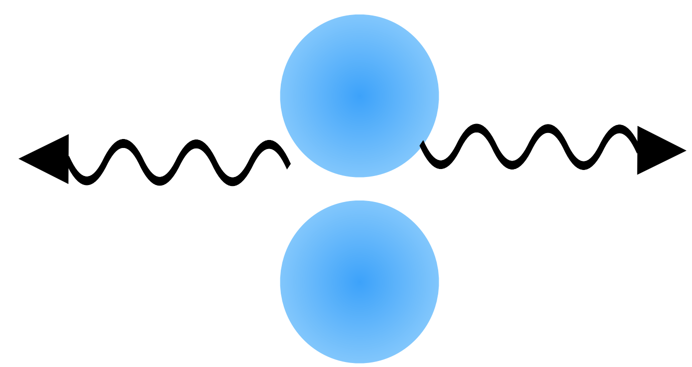
More powers of small couplings ↓

- Superradiant growth BH -> 1



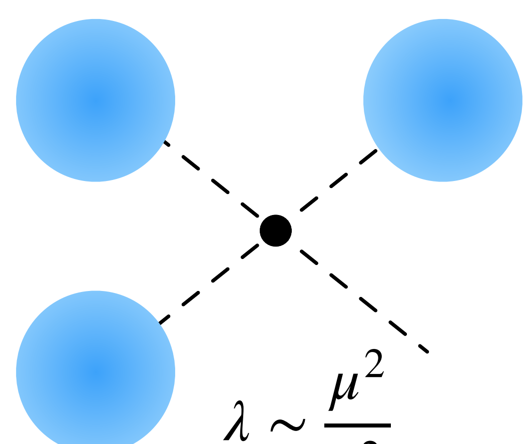
$\dot{N} \sim \mu N$

- Gravitational annihilations: 2->1



$\dot{N} \sim -\mu \frac{\mu^2}{M_{\rm Pl}^2} N^2$

- Self interactions: 3->1



$\lambda \sim \frac{\mu^2}{f_a^2}$

$\dot{N} \sim \mu \frac{\mu^4}{f_{\rm a}^4} N^3$

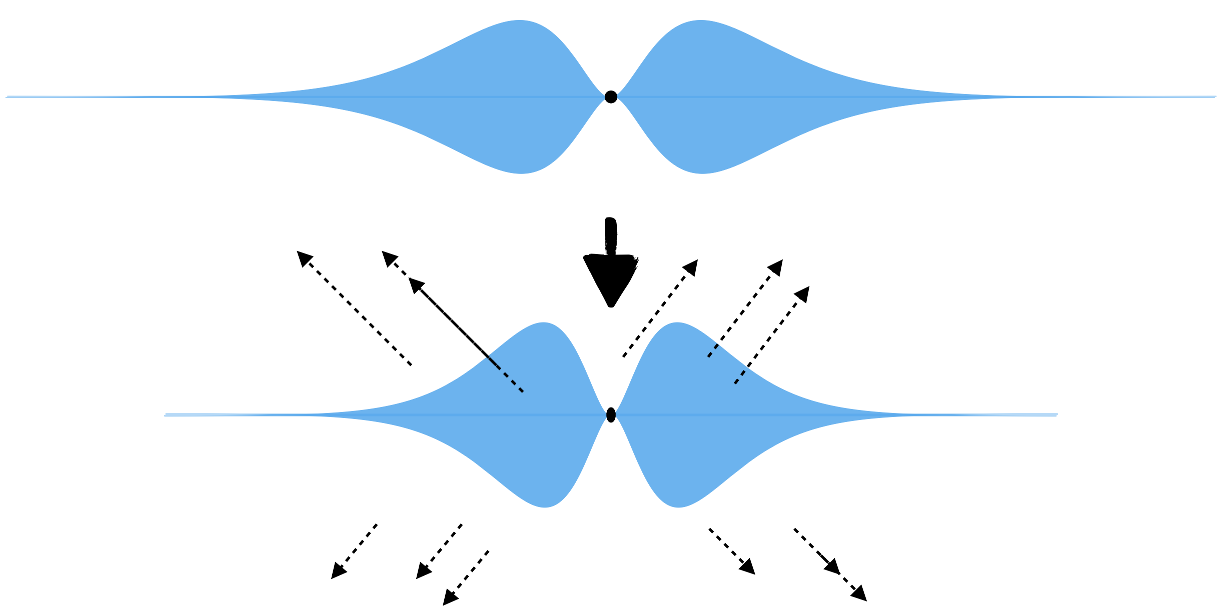
More powers of large occupation numbers ↓

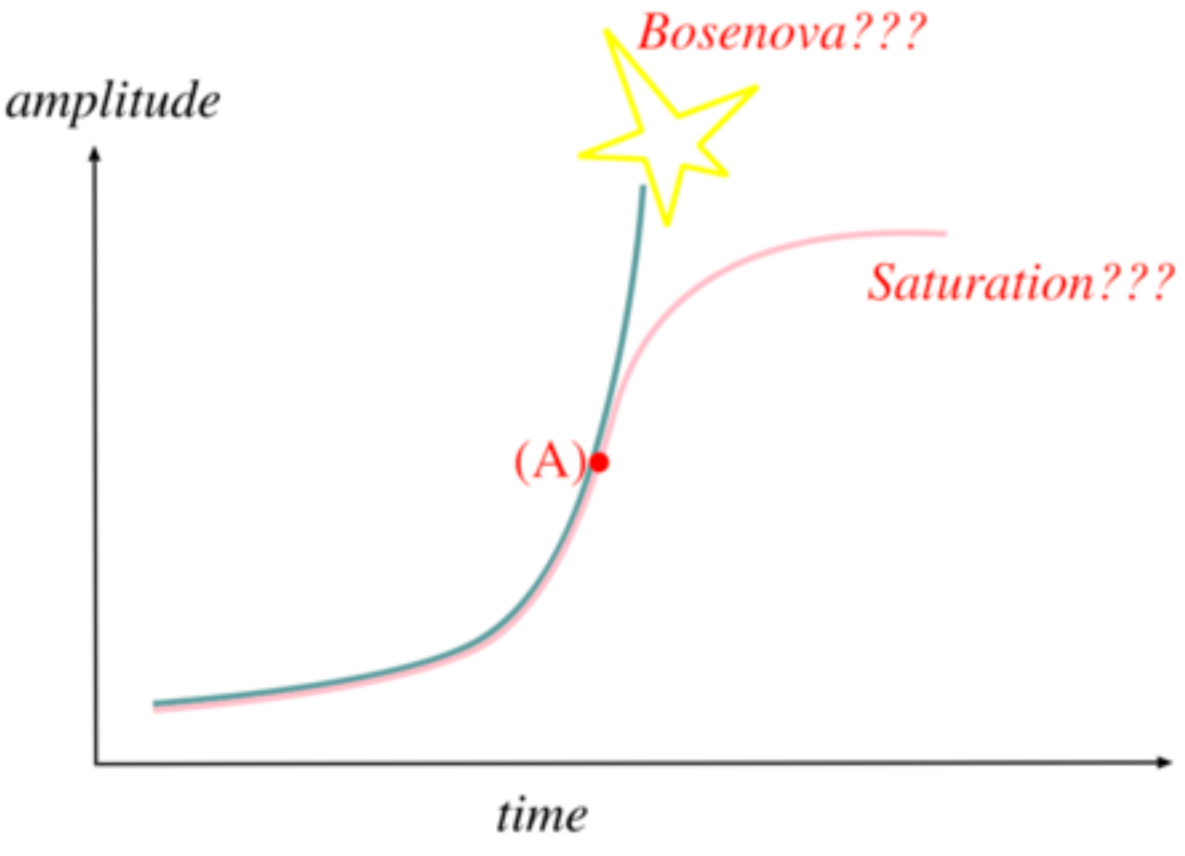
Max particle number ~ ratio of the Planck mass to the axion mass, squared: $N_{\rm max} \sim \frac{M_{\rm Pl}^2}{\mu^2}$

Bosenova

- Attractive self energy can make the cloud shrink and perhaps collapse

Arvanitaki, Dubovsky 2010



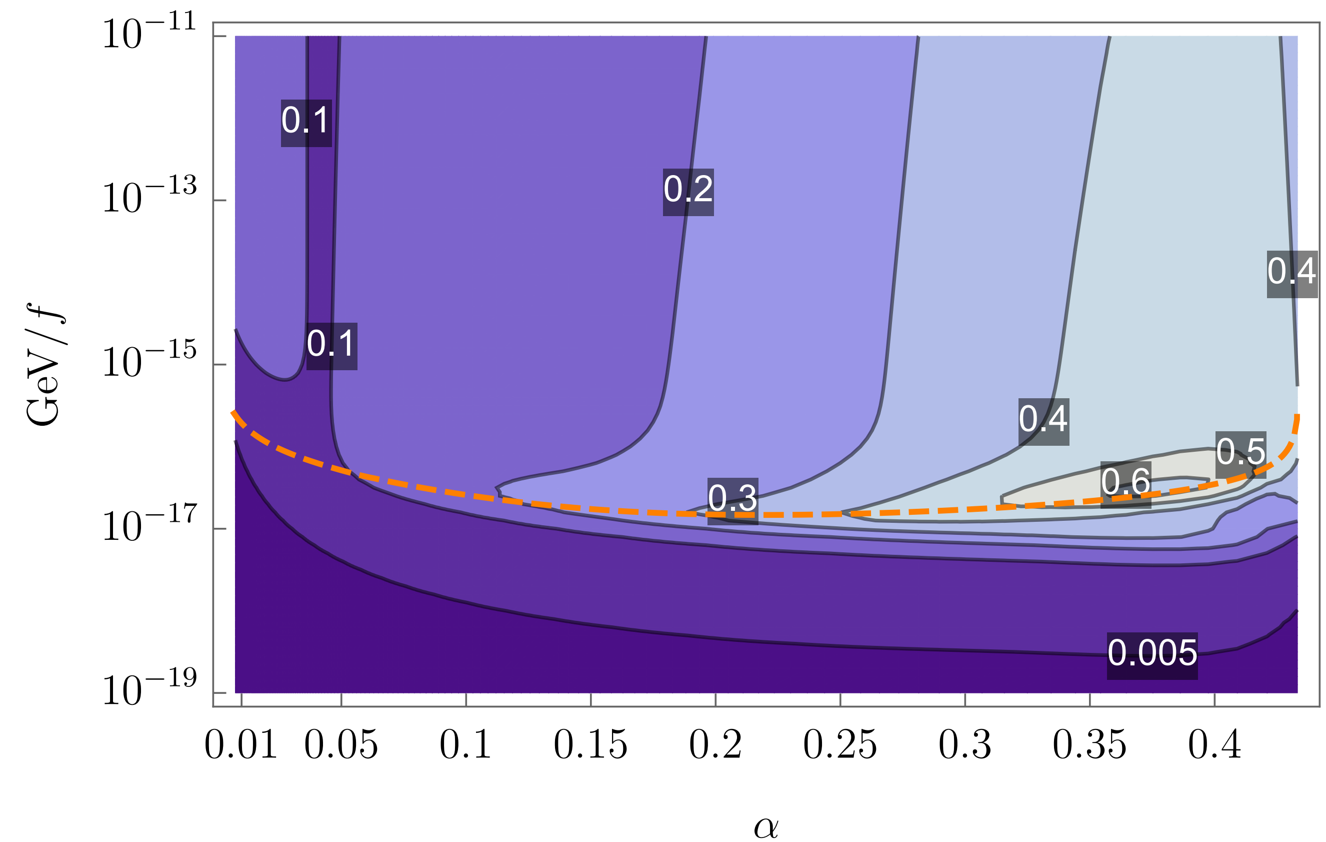


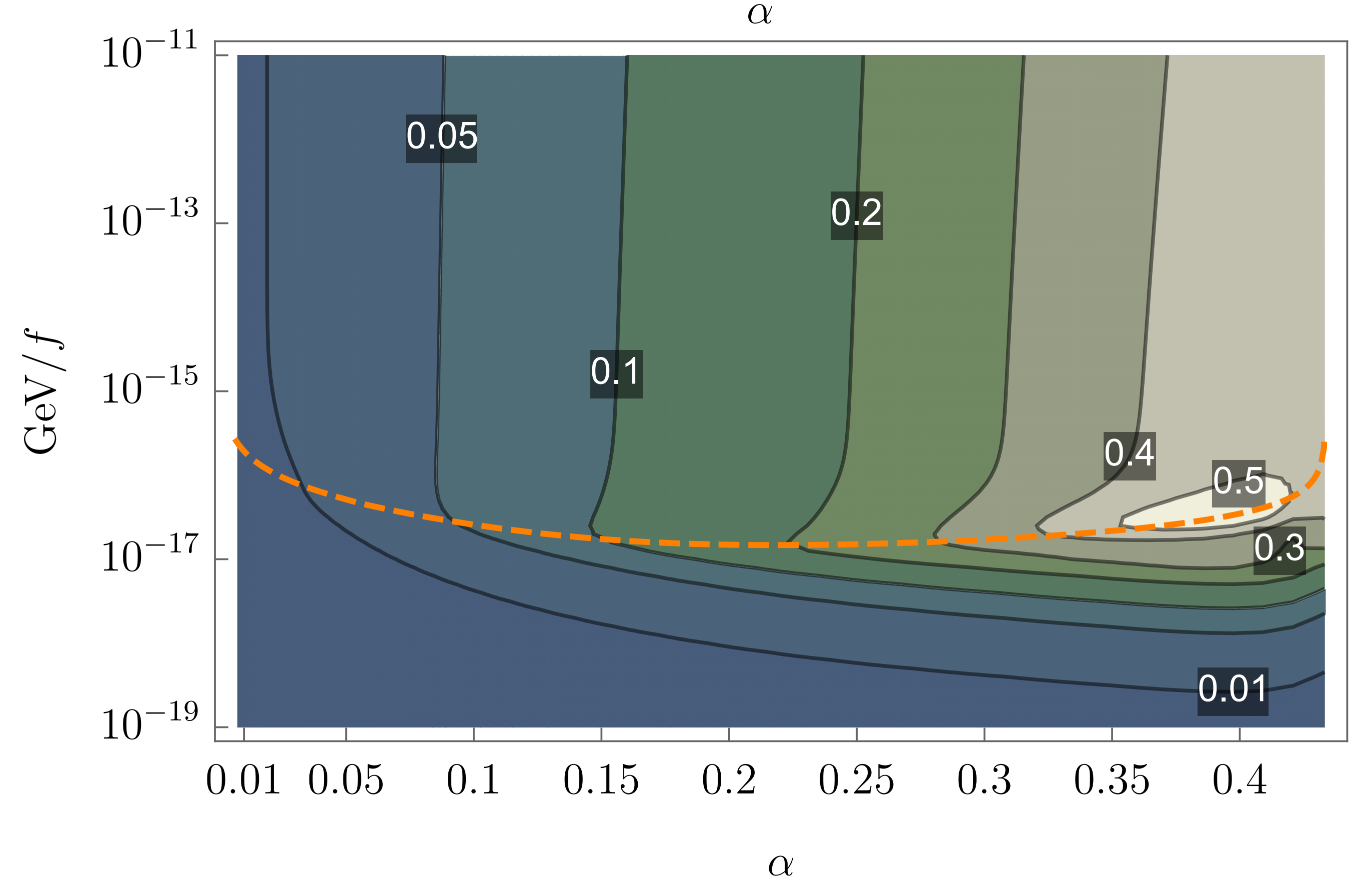
Hirotaka Yoshino, Hideo Kodama 2012

Bosenova

MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

- In perturbative calculations, the occupation number always stays below that which would cause collapse
- a/fa is up to 0.5
- at large alpha, full numerics required to understand evolution





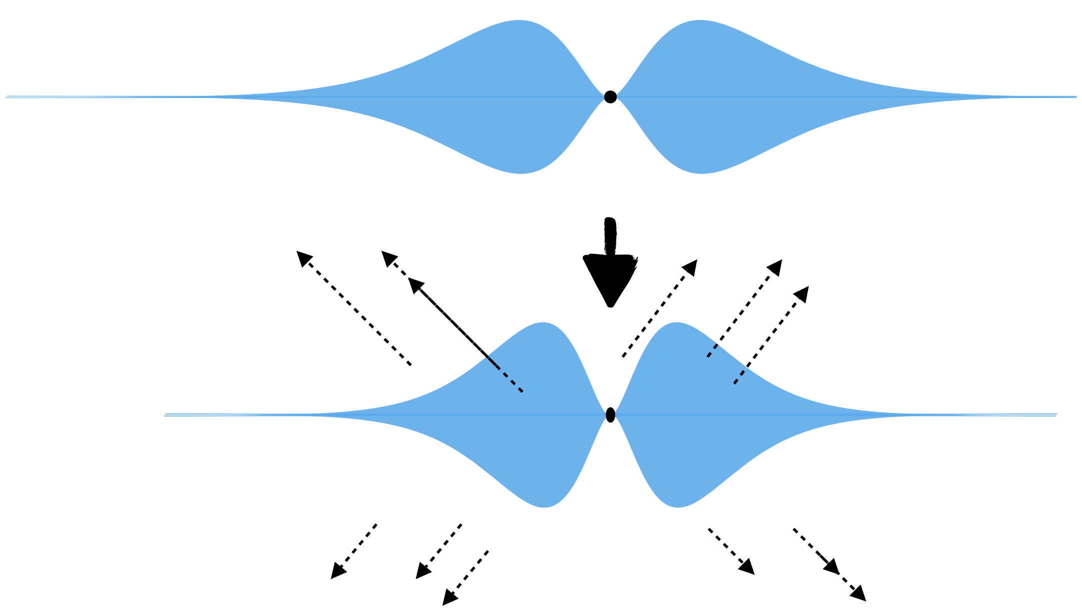
Bosenova

- Attractive self energy can make the cloud shrink and perhaps collapse

$$V(r) = \frac{\alpha^4 M_{pl}^2 \varepsilon}{\mu}\left(\frac{1}{8r^2} - \frac{1}{4r} - \frac{3\alpha^3 \varepsilon M_{pl}^2}{16384 \pi r^3 f_a^2}\right)$$

Arvanitaki, Dubovsky 2010
Yoshino, Kodama 2012

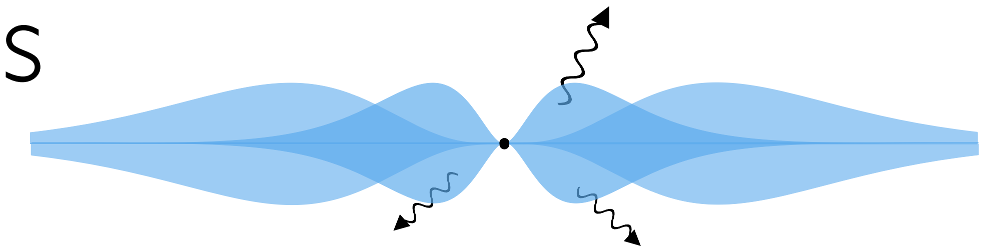
$$r_{\text{extrema}} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{9\alpha^3 \varepsilon_1 {M_{\text{pl}}}^2}{4096 \pi f^2}}$$



$$\varepsilon_{\text{crit}} = \frac{32}{711\alpha^2}\sqrt{75840\pi\left(\frac{f_a}{M_{\text{Pl}}}\right)^2 + 225\alpha^2} - \frac{160}{237\alpha}$$

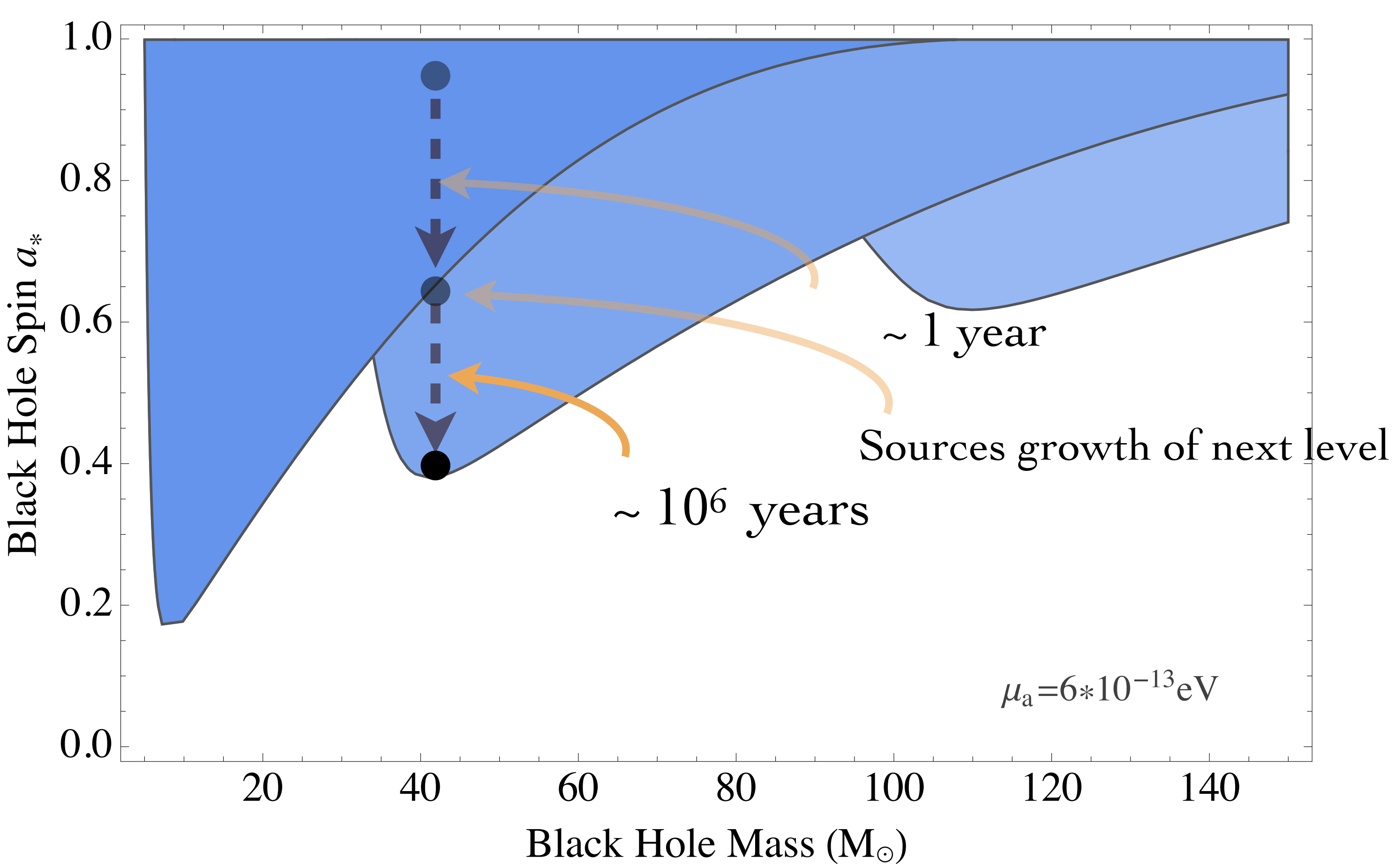
$$\varepsilon_{\max} = \begin{cases} \frac{2\sqrt{2}}{\sqrt{3}} \frac{\sqrt{\gamma_{\inf}\gamma_{\text{SR1}}}}{\gamma_{\text{BH}}} & \gamma_{\text{BH}} > 800\gamma_{\text{SR1}} \\ a_\star(0) - \frac{4\alpha}{1+4\alpha^2} & \gamma_{\text{BH}} < 800\gamma_{\text{SR1}} \end{cases}$$

Self-Interactions

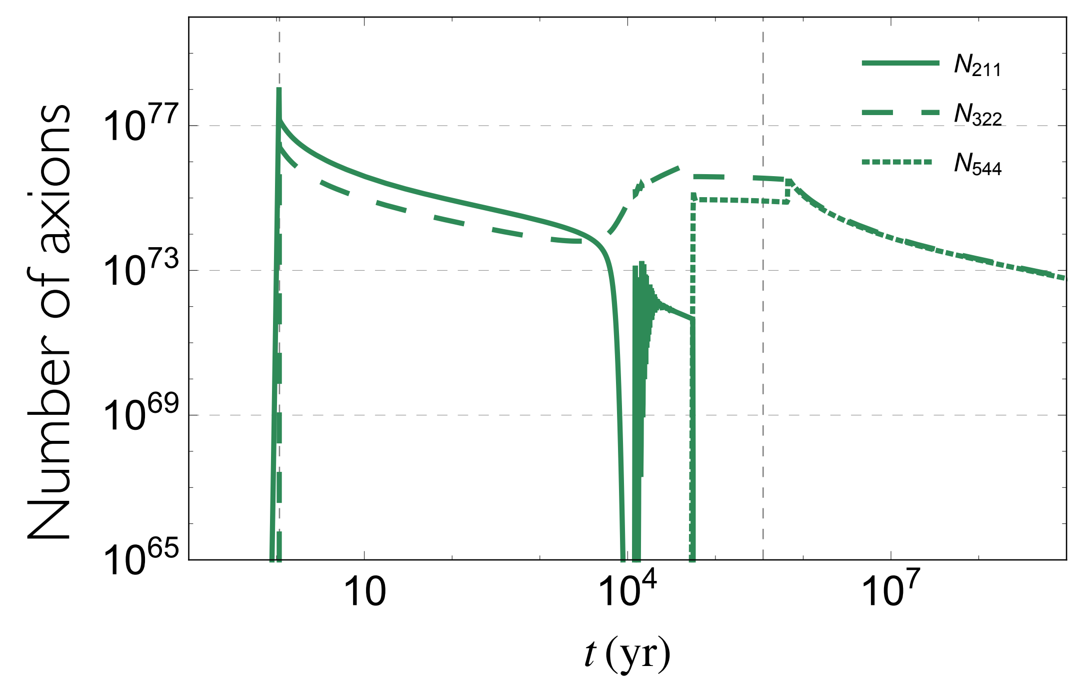


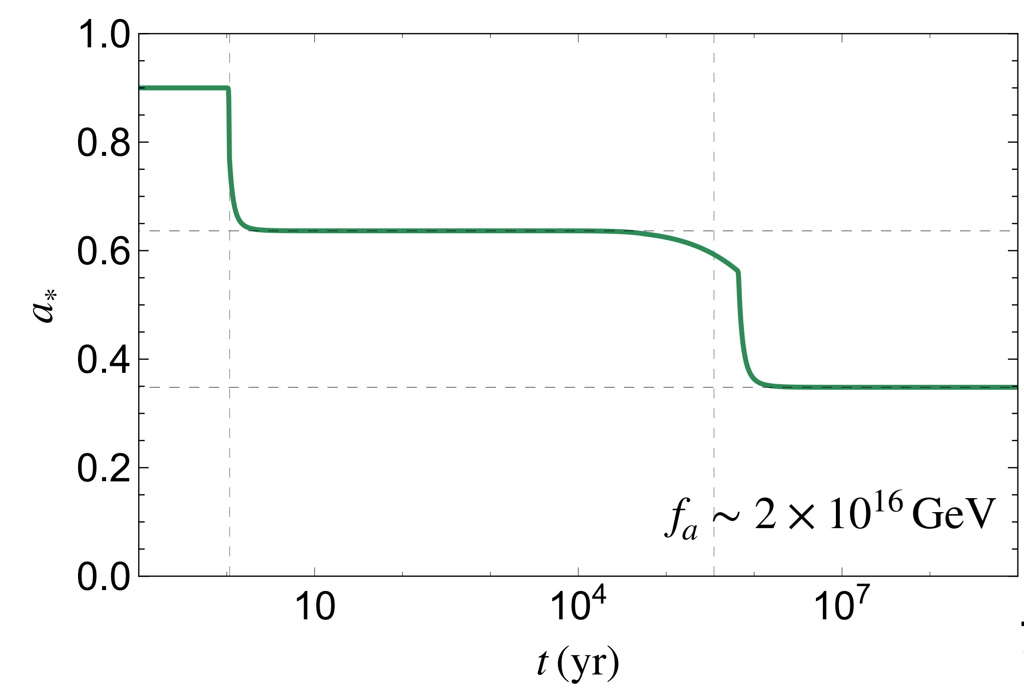
Intermediate self-interactions: $f_a \sim M_{\text{GUT}}$

- BH sources 211
- Population in 211 sources 322

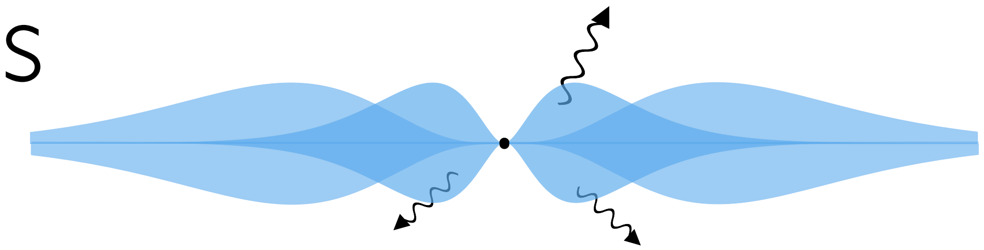


MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*



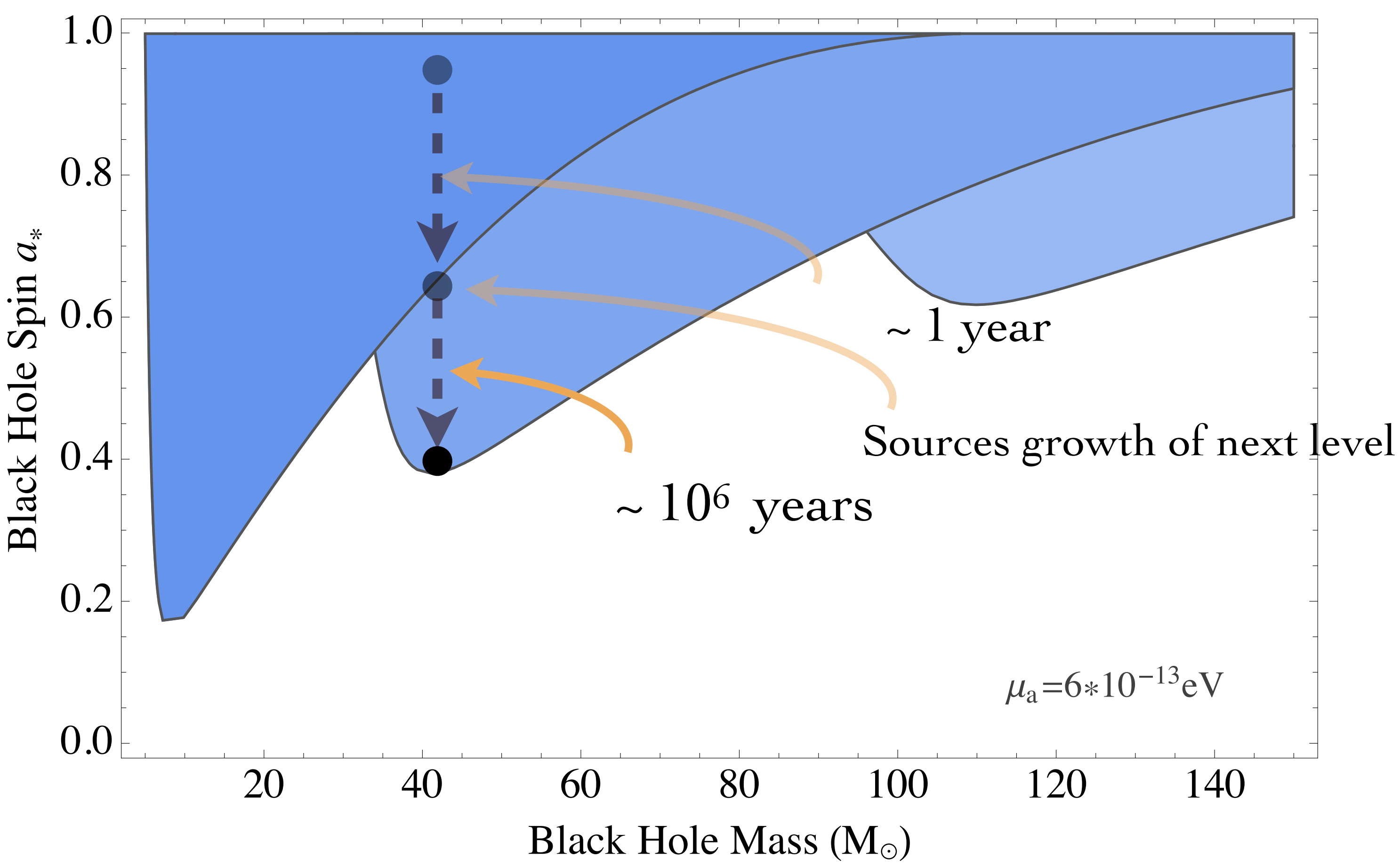


Self-Interactions

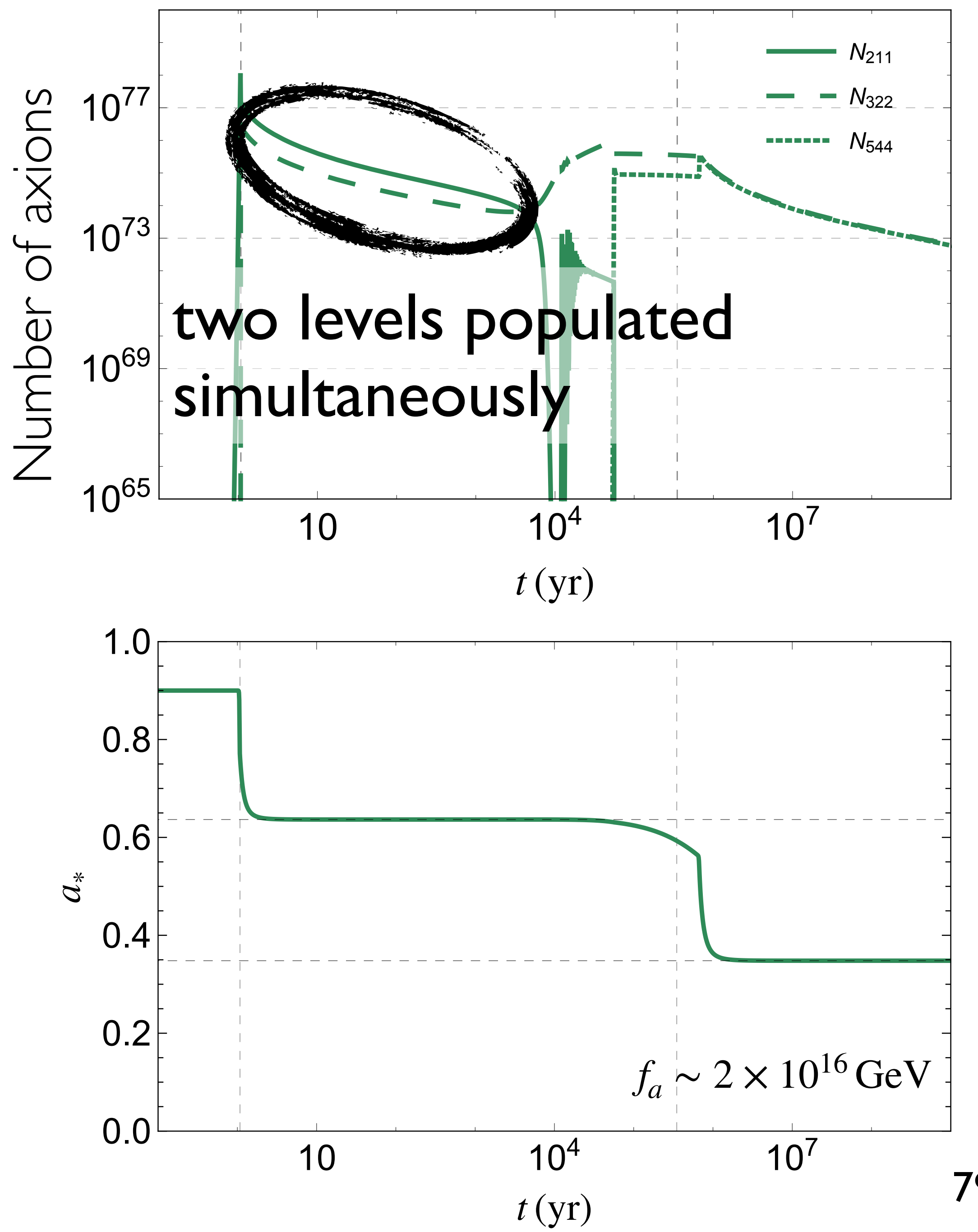


Intermediate self-interactions: $f_a \sim M_{\mathrm{GUT}}$

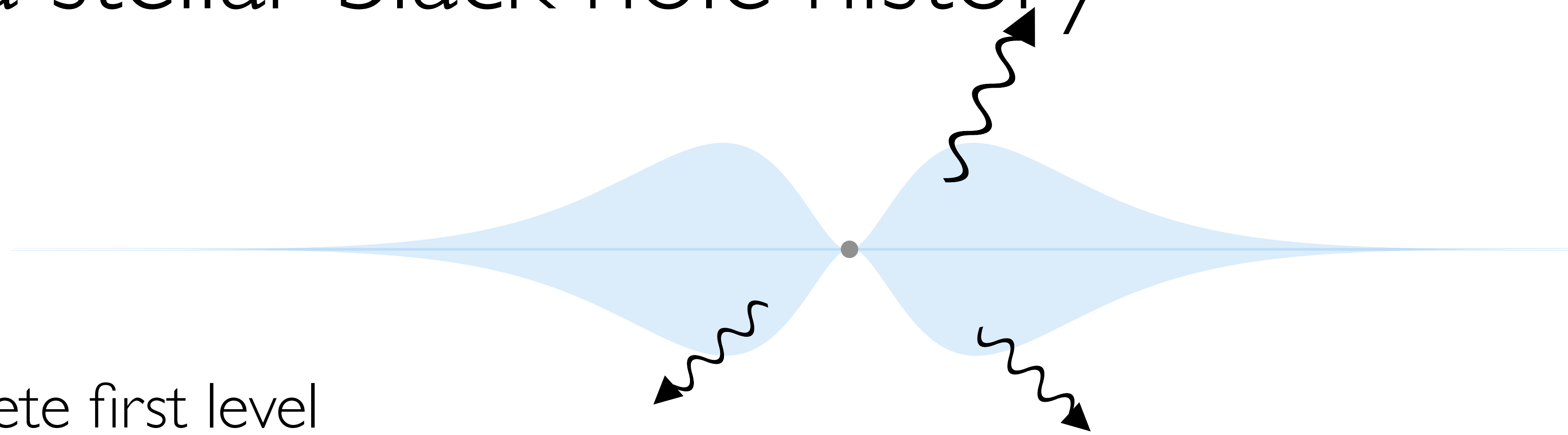
- BH sources 211
- Population in 211 sources 322



MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*



Superradiance: a stellar black hole history



Annihilations to GWs deplete first level

Gravitational waves can be observed in LIGO continuous wave searches

Annihilation rate

$$P_{GW} \sim G_N \omega^2 \overline{T}_{ij}(\omega, k)\overline{T}^*_{ij}(\omega, k) \quad \sim G_N \mu^2 \left| \int N \mu \psi^2 j_\ell(r\omega) dV \right|^2$$

scalar emission

$$\frac{d\langle P\rangle}{d\Omega}(\theta_k, \varphi_k) = 2\frac{\omega_r|\vec{k}|}{(4\pi)^2}\lambda^2|\tilde{f}(\vec{k})|^2,$$

$$\tilde{f}(\vec{k}) = \sum_{lm} Y_l^m(\theta_k, \varphi_k) \int d^3\vec{r}(4\pi)(-i)^l f(\vec{r})\frac{\psi^*_{klm}(\vec{r})}{2k}.$$

Self-Interactions

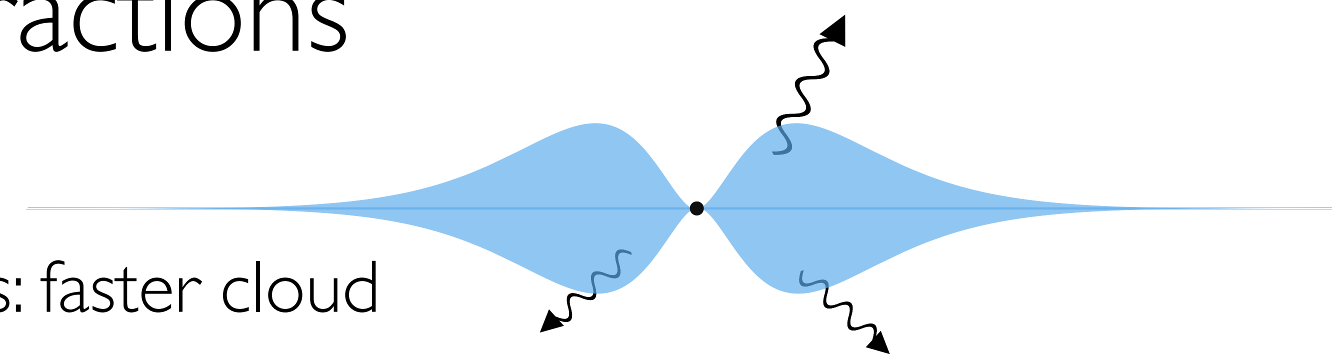
TABLE I. The different rates involved in the evolution of the cloud

Rate	Dimension-full rate Γ (1)	Dimension-less rate γ (3) (in units of μ)
$\Gamma_{211}^{\rm SR}$	$\approx (2\times 10^{-2})\alpha^8(a_* - 2\alpha(1+\sqrt{1-a_*^2}))\mu$	$2\times 10^{-2}\alpha^8(a_* - 2\alpha(1+\sqrt{1-a_*^2}))$
$\Gamma_{322}^{\rm SR}$	$\approx (4\times 10^{-5})\alpha^{12}(a_* - \alpha(1+\sqrt{1-a_*^2}))\mu$	$4\times 10^{-5}\alpha^{12}(a_* - \alpha(1+\sqrt{1-a_*^2}))$
$\Gamma_{433}^{\rm SR}$	$\approx (1\times 10^{-8})\alpha^{16}(a_* - \frac{2}{3}\alpha(1+\sqrt{1-a_*^2}))\mu$	$1\times 10^{-8}\alpha^{16}(a_* - \frac{2}{3}\alpha(1+\sqrt{1-a_*^2}))$
$\Gamma_{544}^{\rm SR}$	$\approx (1\times 10^{-12})\alpha^{20}(a_* - \frac{1}{2}\alpha(1+\sqrt{1-a_*^2}))\mu$	$1\times 10^{-12}\alpha^{20}(a_* - \frac{1}{2}\alpha(1+\sqrt{1-a_*^2}))$
$\Gamma_{211}^{\rm GW,ann}$	$\approx (1\times 10^{-2})\alpha^{12}\left(\frac{\mu}{M_{\rm pl}}\right)^2\mu$	$1\times 10^{-2}\alpha^{14}$
$\Gamma_{211\times 322}^{\rm GW,ann}$	$\approx (1\times 10^{-4})\alpha^{14}\left(\frac{\mu}{M_{\rm pl}}\right)^2\mu$	$1\times 10^{-4}\alpha^{16}$
$\Gamma_{322}^{\rm GW,ann}$	$\approx (3\times 10^{-8})\alpha^{16}\left(\frac{\mu}{M_{\rm pl}}\right)^2\mu$	$3\times 10^{-8}\alpha^{18}$
$\Gamma_{322\to 211}^{\rm GW,tr}$	$\approx (3\times 10^{-6})\alpha^{8}\left(\frac{\mu}{M_{\rm pl}}\right)^2\mu$	$3\times 10^{-6}\alpha^{10}$
$\Gamma_{211\times 211}^{322\times\,\rm BH}$	$\approx (4.3\times 10^{-7})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$4\times 10^{-7}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{211\times 211}^{422\times\,\rm BH}$	$\approx (1.5\times 10^{-7})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$2\times 10^{-7}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{211\times 322}^{433\times\rm BH}$	$\approx (9.1\times 10^{-8})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$9\times 10^{-8}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{322\times 322}^{544\times\,\rm BH}$	$\approx (1.9\times 10^{-9})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$2\times 10^{-9}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{211\times 433}^{544\times\rm BH}$	$\approx (1.1\times 10^{-9})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$1\times 10^{-9}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{322\times 433}^{655\times\,\rm BH}$	$\approx (2.8\times 10^{-10})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$3\times 10^{-10}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{211\times 544}^{655\times\rm BH}$	$\approx (3.6\times 10^{-12})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$3\times 10^{-12}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{433\times 433}^{766\times\rm BH}$	$\approx (2.1\times 10^{-10})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$2\times 10^{-10}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{433\times 544}^{877\times\rm BH}$	$\approx (5.2\times 10^{-12})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$5\times 10^{-12}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{544\times 544}^{988\times\rm BH}$	$\approx (1.6\times 10^{-12})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$2\times 10^{-12}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{544\times 655}^{1099\times\rm BH}$	$\approx (5.6\times 10^{-13})\alpha^7\lambda^2(1+\sqrt{1-a_*^2})\mu$	$5\times 10^{-13}\alpha^{11}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Gamma_{211\times 422}^{433\times 200}$	$\approx (1.1\times 10^{-9})\alpha^3\lambda^2(1+\sqrt{1-a_*^2})\mu$	$1\times 10^{-9}\alpha^{7}\left(\frac{M_{\rm pl}}{f_a}\right)^4(1+\sqrt{1-a_*^2})$
$\Delta\omega_{211}^{211}$	$\approx -(1.2\times 10^{-4})\lambda N_{211}\alpha^3\mu$	
$\Delta\omega_{211}^{322}$	$\approx -(3.5\times 10^{-5})\lambda N_{322}\alpha^3\mu$	

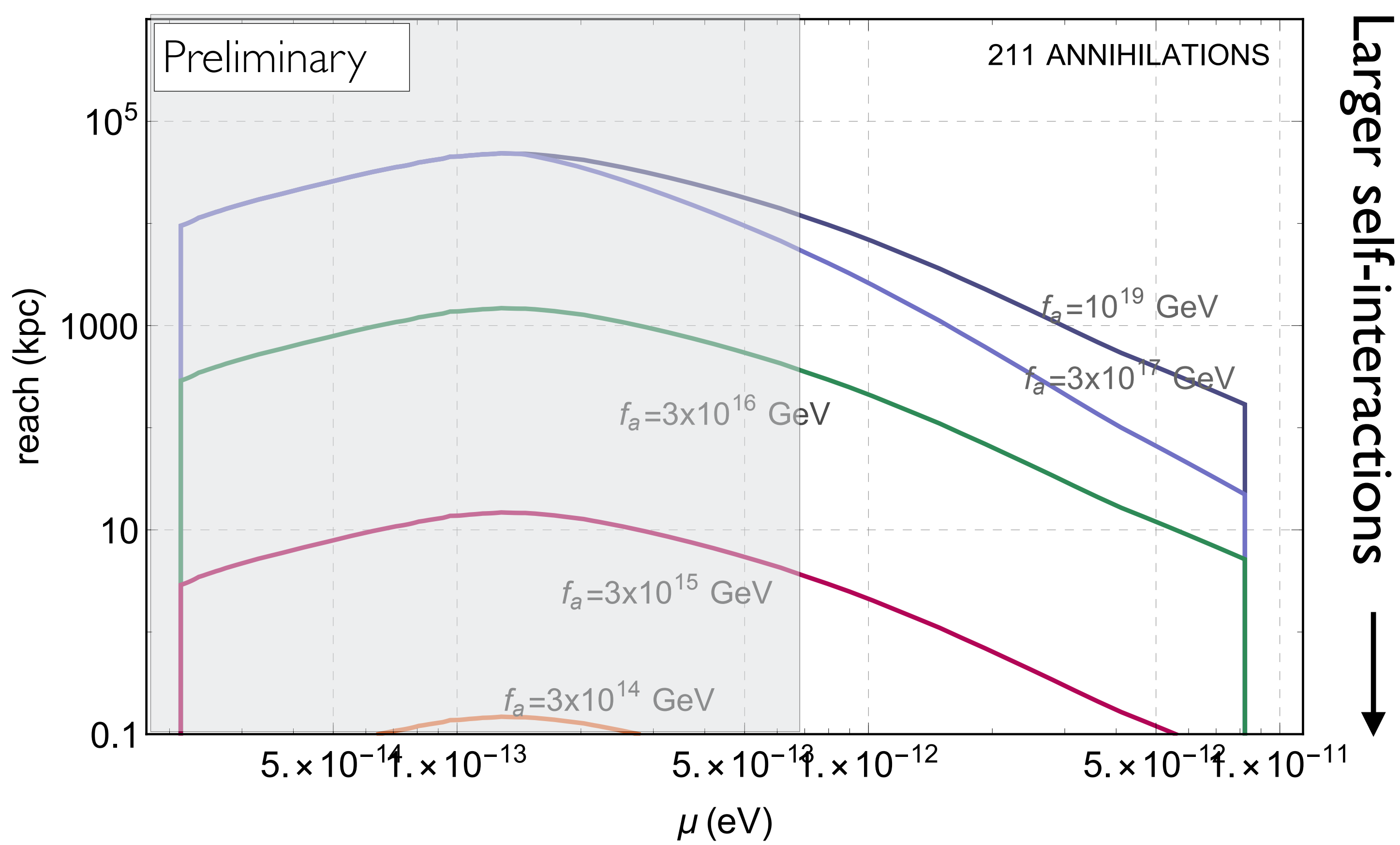
TABLE II. The different rates involved in the evolution of the cloud

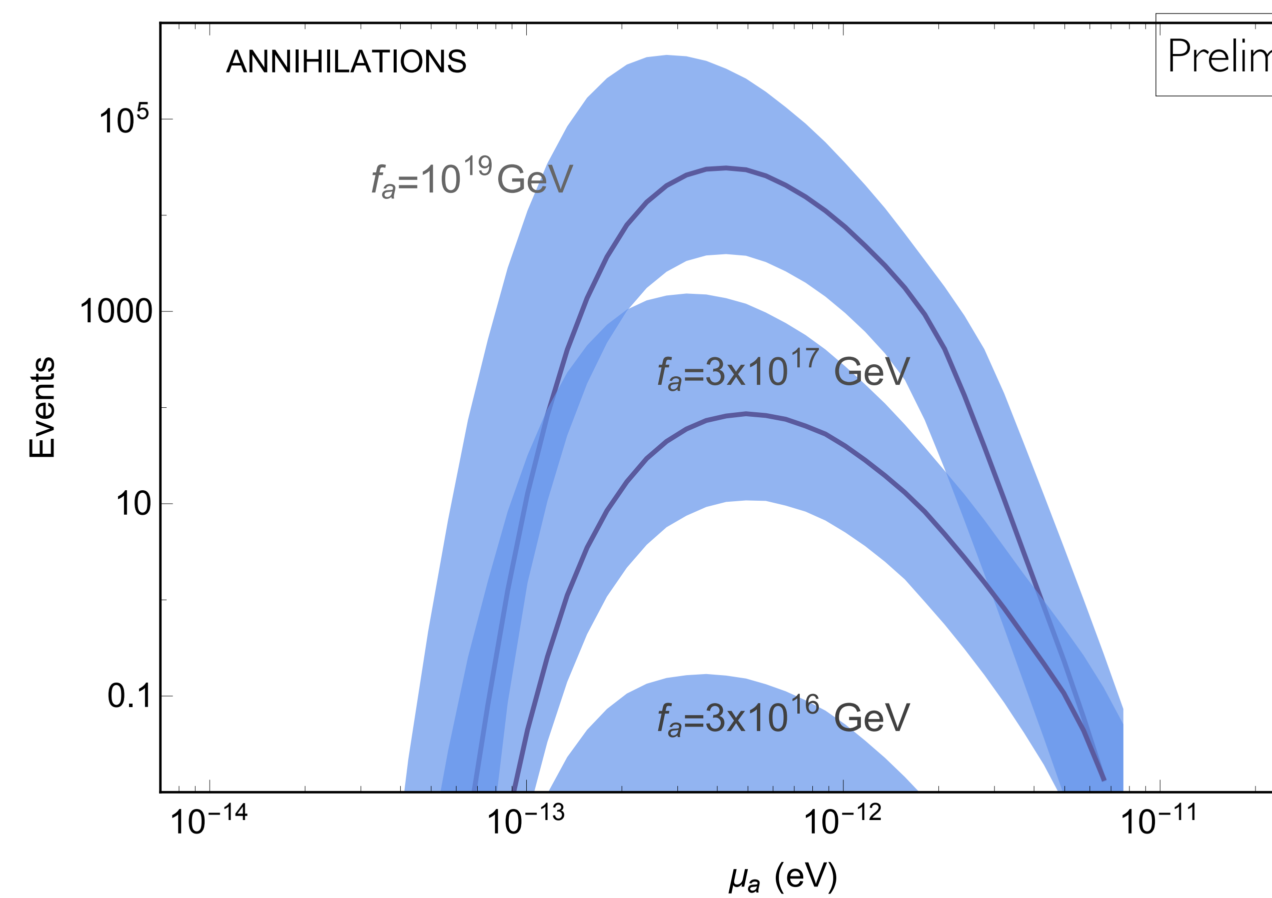
Rate	Dimension-full rate Γ (1)	Dimension-less rate γ (3) (in units of μ)
$\Gamma_{211\times 211}^{100\times\infty}$	$\approx (1.3\times 10^{-7})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{211\times 322}^{100\times\infty}$	$\approx (8.5\times 10^{-9})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{322\times 322}^{100\times\infty}$	$\approx (1.1\times 10^{-10})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{322\times 322}^{211\times\infty}$	$\approx (1.1\times 10^{-8})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{322\times 433}^{211\times\infty}$	$\approx (2.6\times 10^{-9})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{433\times 433}^{211\times\infty}$	$\approx (9.2\times 10^{-11})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{322\times 544}^{211\times\infty}$	$\approx (6.1\times 10^{-11})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{433\times 544}^{211\times\infty}$	$\approx (1.9\times 10^{-11})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{544\times 544}^{211\times\infty}$	$\approx (4.2\times 10^{-13})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{544\times 544}^{322\times\infty}$	$\approx (4.4\times 10^{-11})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{433\times 544}^{322\times\infty}$	$\approx (7.8\times 10^{-10})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{322\times 322}^{21-1\times\infty}$	$\approx (2.3\times 10^{-10})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 322}^{211\times\infty}$	$\approx (7.3\times 10^{-13})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 433}^{211\times\infty}$	$\approx (4.6\times 10^{-13})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 544}^{211\times\infty}$	$\approx (6.9\times 10^{-14})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 655}^{211\times\infty}$	$\approx (1.1\times 10^{-15})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 433}^{322\times\infty}$	$\approx (3.7\times 10^{-11})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 544}^{322\times\infty}$	$\approx (1.6\times 10^{-11})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{655\times 655}^{322\times\infty}$	$\approx (6.2\times 10^{-13})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{766\times 766}^{433\times\infty}$	$\approx (5.6\times 10^{-13})\alpha^4\lambda^2\mu$	$\alpha^8\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{211}^{2\to 1}$(cubic)	$\approx (1.9\times 10^{-4})\alpha^{12}\frac{\mu^3}{f^2}$	$2\times 10^{-4}\alpha^{14}\left(\frac{M_{\rm pl}}{f}\right)^2$
$\Gamma_{211}^{3\to 1}$	$\approx (7\times 10^{-9})\alpha^{17}\lambda^2\mu$	$7\times 10^{-9}\alpha^{21}\left(\frac{M_{\rm pl}}{f_a}\right)^4$
$\Gamma_{322}^{3\to 1}$	$\approx (6\times 10^{-14})\alpha^{23}\lambda^2\mu$	$6\times 10^{-14}\alpha^{27}\left(\frac{M_{\rm pl}}{f_a}\right)^4$

Self-Interactions



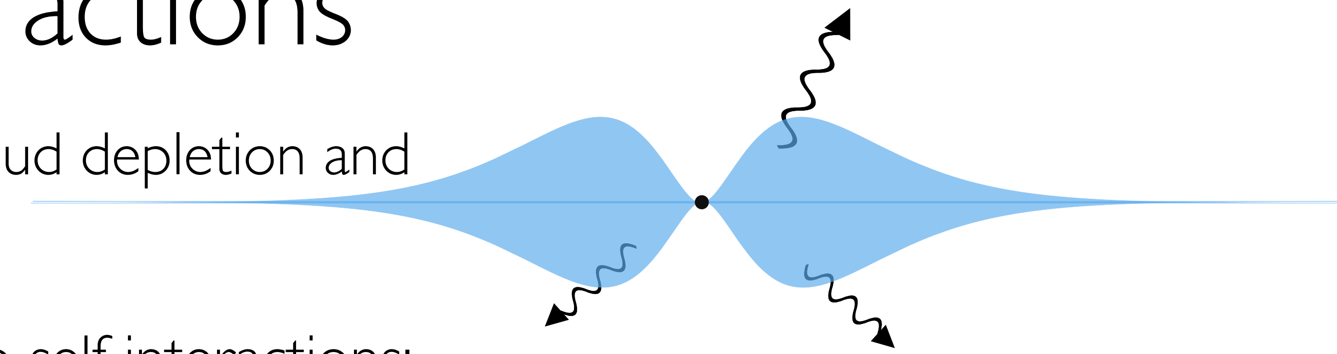
- New source of energy loss to scalar waves: faster cloud depletion and shorter signals
- Evolution of first level capped at smaller value due to self interactions: gravitational wave **annihilation** power suppressed at low fa





MB, M. Galanis, R. Lasenby, O. Simon, *(in prep)*

Self-Interactions



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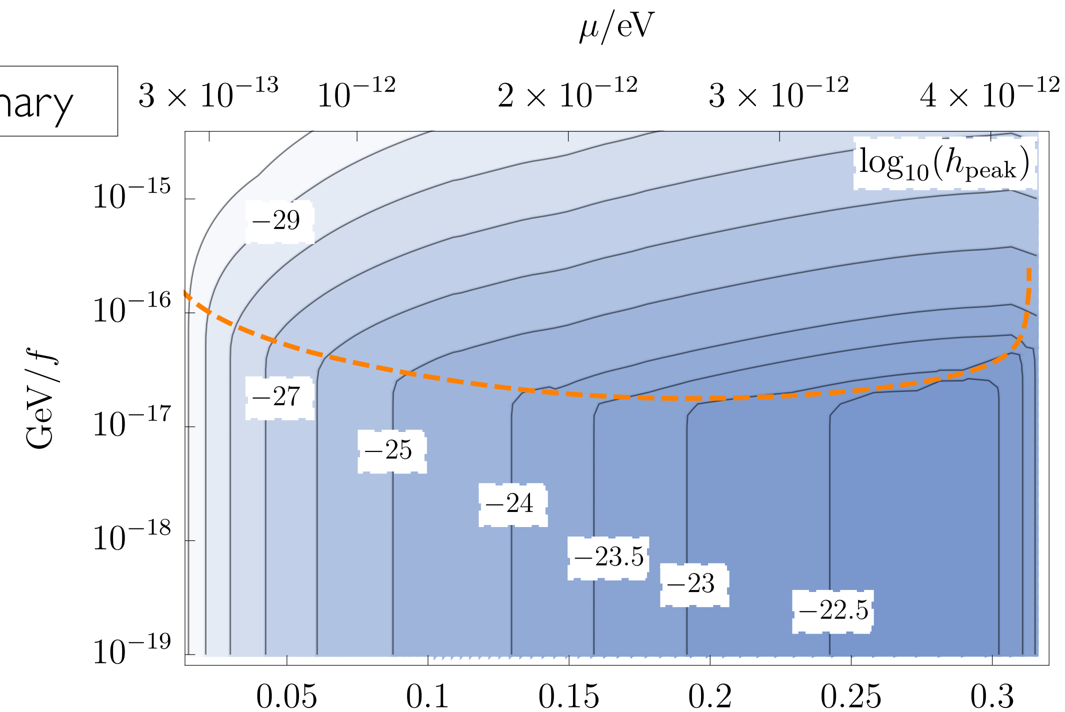
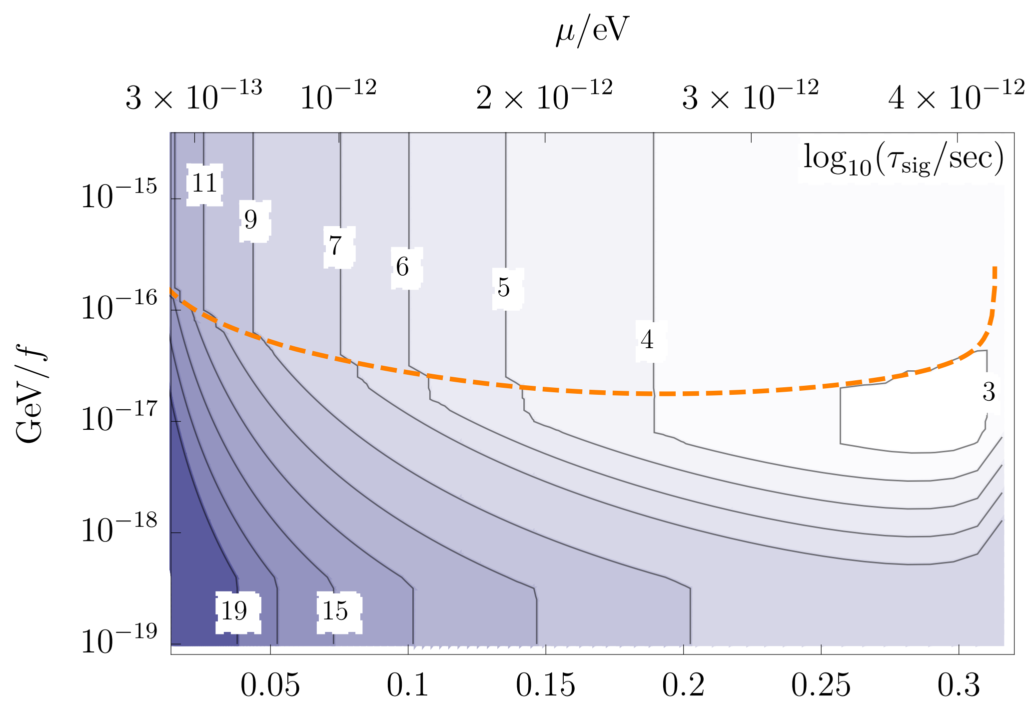
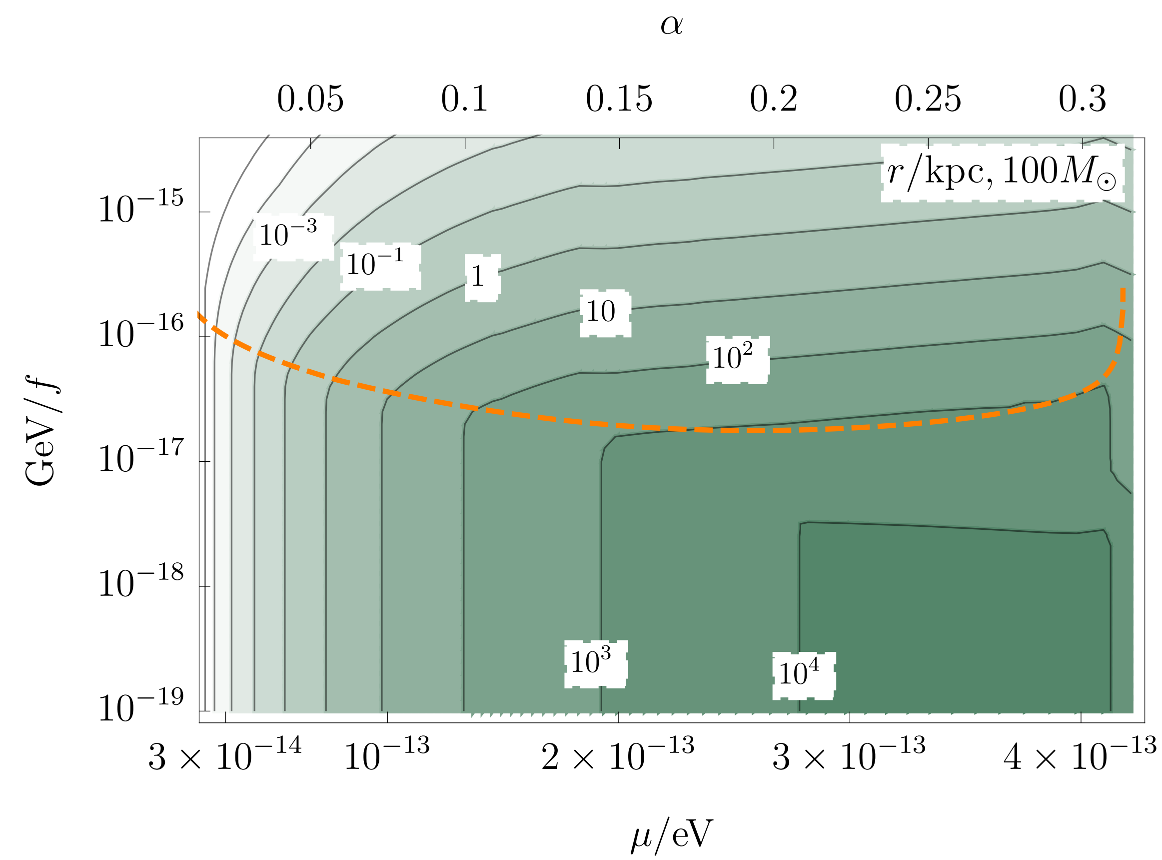
Preliminary





Larger self-interactions →



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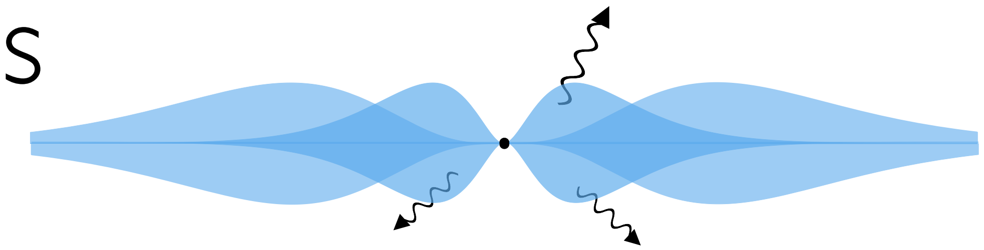
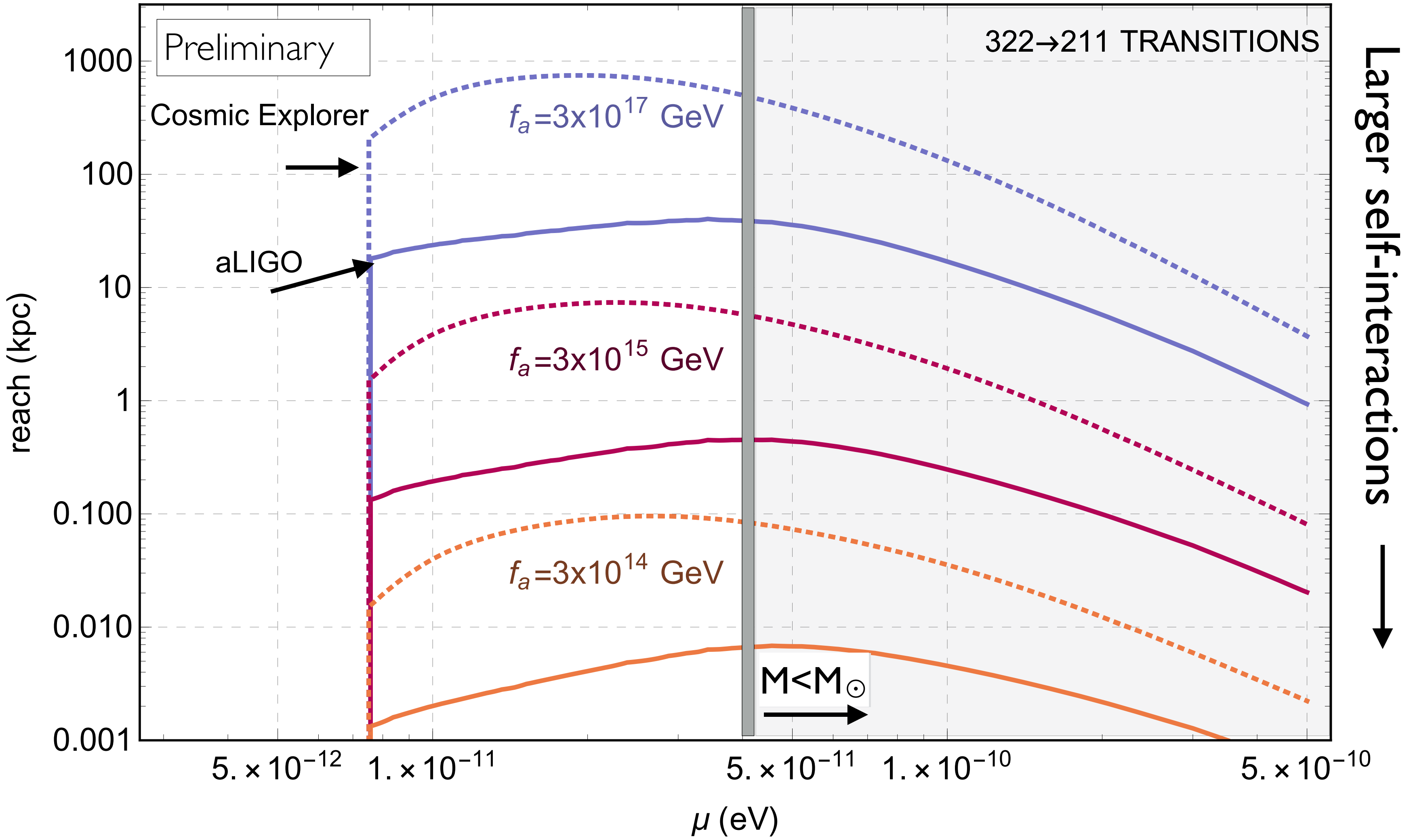
Self-Interactions



- Two (or more) levels populated simultaneously: new signatures
- Gravitational **transitions** between two levels: larger power than annihilations
- Scalar waves are a new source of energy loss: faster cloud depletion and shorter signals



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